AGARD-CP-587

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD CONFERENCE PROCEEDINGS 587

Aircraft Fire Safety

(la Sécurité incendie des aéronefs)

Papers presented at the Propulsion and Energetics Panel (PEP) 88th Symposium, held in Dresden, Germany, 14-17 October 1996.

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization

Organisation du Traité de l'Atlantique Nord

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— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

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Aircraft Fire Safety

(AGARD CP-587)

Executive Summary

Aircraft fire safety, despite its importance, is not a subject frequently covered, and the Propulsion and Energetics Panel of AGARD has taken the initiative to focus attention more specifically on this topic which covers a wide diversity of subjects. A first symposium was held in Italy in 1975 (CP 166), and a second symposium was held in Portugal in 1989 (CP 476).

Since then the aircraft fire safety issue has evolved further, particularly in response to environmental considerations, an increased perception of fire hazards, and new threats and challenges. The HALON replacement issue, the post-crash management of burnt materials, the risk and effects of onboard explosions and fires in aircraft, and the use of military transport aircraft over potentially hostile areas for humanitarian and peacekeeping operations, are examples.

Much research on aircraft fire safety is aimed at civil transport aircraft but is also applicable to military transport aircraft. In a recent accident involving a military transport aircraft, most people on board were not severely hurt by the impact. However, thirty-four of them died due to the fire that broke out after the crash landing.

There is a lot of work underway for HALON replacement which is presently used for onboard fire suppression whilst aiming at comparable safety and acceptable toxicity levels. Water spray fire protection systems may become a cost-effective option. On-Board Inert Gas Generation Systems (OBIGGS) are very efficient for the suppression of fuel tank fires.

The concern for the fire safety of structures and materials has expanded from the cabin interior to the burn-through resistance of the fuselage structure and parts of the engine. These activities will have very high application potential for military planes for on-board fire protection as well as survival from post crash external fuel fires.

There are still essential deficiencies in knowledge. Analysis of accidents and incidents without damage, and of potential fire hazards, and research into the cause of death (fire, smoke, or injury), smoke toxicity and human tolerance to intoxication and heat, still needs to be pursued further.

The work on passenger competitive behaviour during cabin evacuation has resulted in highly realistic computer models. In the longer term, computer models could even replace evacuation demonstrations for certification.

The present symposium certainly contributed to the exchange of information and gave the participants an opportunity to establish new contacts. Further international cooperation and exchange amongst those involved in aircraft safety must be enhanced, particularly between the civil and military sectors. A recommendation was put forward that AGARD PEP should organise an aircraft fire safety symposium once every 3 to 5 years rather than every 7 years. The Program Committee Chairman is confident that this symposium contributed to the further improvement of aircraft fire safety.

La sécurité incendie des aéronefs
(AGARD CP-587)

Synthèse

Malgré son importance, le sujet de la sécurité incendie des aéronefs n'est pas souvent abordé. Ainsi, le Panel de Propulsion et d'Energétique de l'AGARD a décidé de se pencher plus particulièrement sur les multiples aspects de cette question. Un premier symposium sur ce thème a été organisé par le Panel en Italie (1975 - CP166) et un deuxième au Portugal (1989 - CP476).

Depuis lors, le sujet de la sécurité incendie des aéronefs a pris plus d'importance, notamment sous l'effet de considération écologiques, de la perception accrue des risques d'incendie, des nouvelles menaces et des nouveaux défis. La question du remplacement du Halon, la gestion post-incendie des matériaux brûles, le risque et les effets d'explosions et d'incendies à bord et l'utilisation d'avions de transport militaires dans des zones hostiles pour des opérations humanitaires et de maintien de la paix en sont des exemples.

Une grande partie des travaux de recherche effectués sur la sécurité incendie des aéronefs est consacrée aux avions de transport civils, mais elle est également applicable aux avions de transport militaires. Lors d'un accident récent concernant un avion de transport militaire, la plupart des personnes à bord n'a reçu que des blessures d'ordre mineur suite à l'impact. Cependant, 34 personnes ont péri dans l'incendie qui s'est déclaré suite à l'aterrissage forcé de l'appareil.

Beaucoup d'efforts sont faits actuellement pour remplacer le halon utilisé pour l'extinction des incendies à bord, tout en maintenant des niveaux de sécurité et de toxicité comparables. Des systèmes de pulvérisation d'eau pourraient représenter une option rentable. Des systèmes de génération de gaz inertes embarqués sont très performants en cas d'incendie de réservoir de carburant.

La préoccupation de la protection incendie des structures et matériaux, qui ne concernait initialement que la cabine, a évolué pour inclure aujourd'hui la résistance à l'incendie de la structure du fuselage et de certains éléments du moteur. Ces activités devraient déboucher sur de nombreuses applications dans le domaine de la protection incendie embarquée des aéronefs militaires, ainsi que la survie en cas d'incendie suite à un écrasement.

Il existe encore des lacunes fondamentales dans nos connaissances dans ce domaine. Il y a lieu de poursuivre plus avant l'analyse des accidents et incidents sans dommages, les risques d'incendie potentiels, les recherches sur les causes des décès (conflagration, suffocation, lésions), sur la toxicité, ainsi que sur la tolérance de l'organisme humain vis à vis de l'intoxication et de la chaleur.

Les travaux réalisés sur le comportement des passagers lors des évacuations d'urgence ont permis d'établir des modèles informatiques hautement réalistes. A terme, il est même envisageable que ces modèles informatiques remplacent les démonstrations des procédures d'évacuation organisées dans le cadre de la certification.

Indiscutablement, ce symposium a permis des échanges d'information fructueux et a offert aux participants l'occasion d'établir de nouveaux contacts. Pourtant, il y a lieu d'améliorer la coopération et les échanges entre ceux qui sont impliqués dans la sécurité des aéronefs et en particulier entre les secteurs civils et militaires. La recommandation a été faite que l'AGARD organise un symposium sur la sécurité incendie des aéronefs tous les 3 à 5 ans, plutôt que tous les 7 ans. Le Président du comité du programme est convaincu de l'importance de la contribution du symposium à l'amélioration de la sécurité incendie des aéronefs.

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AGARD CP 392, January 1986

Advanced Instrumentation for Aero Engine Components
AGARD CP 399, November 1986

Engine Response to Distorted Inflow Conditions
AGARD CP 400, March 1987

Transonic and Supersonic Phenomena in Turbomachines
AGARD CP 401, March 1987

Advanced Technology for Aero Engine Components
AGARD CP 421, September 1987

Combustion and Fuels in Gas Turbine Engines
AGARD CP 422, June 1988

Engine Condition Monitoring — Technology and Experience
AGARD CP 448, October 1988

Application of Advanced Material for Turbomachinery and Rocket Propulsion
AGARD CP 449, March 1989

Combustion Instabilities in Liquid-Fuelled Propulsion Systems
AGARD CP 450, April 1989

Aircraft Fire Safety
AGARD CP 467, October 1989

Unsteady Aerodynamic Phenomena in Turbomachines
AGARD CP 468, February 1990

Secondary Flows in Turbomachines
AGARD CP 469, February 1990

Hypersonic Combined Cycle Propulsion
AGARD CP 479, December 1990

Low Temperature Environment Operations of Turboengines (Design and User's Problems)
AGARD CP 480, May 1991

CFD Techniques for Propulsion Applications
AGARD CP 510, February 1992

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AGARD CP 511, July 1992

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Airbreathing Propulsion for Missiles and Projectiles
AGARD CP 526, September 1992

Heat Transfer and Cooling in Gas Turbines
AGARD CP 527, February 1993

Fuels and Combustion Technology for Advanced Aircraft Engines
AGARD CP 536, September 1993

Technology Requirements for Small Gas Turbines
AGARD CP 537, March 1994

Erosion, Corrosion and Foreign Object Damage Effects in Gas Turbines
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Environmental Aspects of Rocket and Gun Propulsion
AGARD CP 559, February 1995

Loss Mechanisms and Unsteady Flows in Turbomachines
AGARD CP 571, January 1996

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Recommended Practices for Measurement of Gas Path Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components *(Results of Working Group 19)*
AGARD AR 245, June 1990

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Test Cases for Engine Life Assessment Technology *(Results of Working Group 20)*
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Terminology and Assessment Methods of Solid Propellant Rocket Exhaust Signatures *(Results of Working Group 21)*
AGARD AR 287, February 1993

Guide to the Measurement of the Transient Performance of Aircraft Turbine Engines and Components *(Results of Working Group 23)*
AGARD AR 320, March 1994

Experimental and Analytical Methods for the Determination of Connected — Pipe Ramjet and Ducted Rocket Internal Performance *(Results of Working Group 22)*
AGARD AR 323, July 1994

Recommended Practices for the Assessment of the Effects of Atmospheric Water Ingestion on the Performance and Operability of Gas Turbine Engines *(Results of Working Group 24)*
AGARD AR 332, September 1995

LECTURE SERIES (LS)

Engine Airframe Integration for Rotorcraft
AGARD LS 148, June 1986

Design Methods Used in Solid Rocket Motors
AGARD LS 150, April 1987
AGARD LS 150 (Revised), April 1988

Blading Design for Axial Turbomachines
AGARD LS 167, June 1989

Comparative Engine Performance Measurements
AGARD LS 169, May 1990

Combustion of Solid Propellants
AGARD LS 180, July 1991

Steady and Transient Performance Prediction of Gas Turbine Engines
AGARD LS 183, May 1992

Rocket Motor Plume Technology
AGARD LS 188, June 1993

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AGARD LS 194, December 1993

Turbomachinery Design Using CFD
AGARD LS 195, May 1994

Mathematical Models of Gas Turbine Engines and their Components
AGARD LS 198, December 1994

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Measurement Uncertainty within the Uniform Engine Test Programme
AGARD AG 307, May 1989

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AGARD AG 316, September 1990

Advanced Methods for Cascade Testing
AGARD AG 328, August 1993

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Application of Modified Loss and Deviation Correlations to Transonik Axial Compressors
AGARD R 745, June 1990

Rotorcraft Drivetrain Life Safety and Reliability
AGARD R 775, June 1990

Propulsion and Energy Issues for the 21st Century
AGARD R 824, March 1997

Impact Study on the use of JET A Fuel in Military Aircraft during Operations in Europe
AGARD R 801, January 1997

The Single Fuel Concept and Operation Desert Shield/Storm
AGARD R 810, January 1997 *(NATO Unclassified)*

Theme

This symposium on Aircraft Fire Safety offers a unique platform where all disciplines involved are brought together and gives the opportunity to interact with each other. The symposium covers both civil and military aircraft fire safety aspects with respect to on-board and post-crash fires, structural and material characteristics related to fire resistance, smoke toxicity, passenger/crew protection and behaviour during emergency evacuations.

In 1989 a very well attended symposium was organized by PEP on the same topic. Since then new developments have taken place of which the banning of Halon as a fire extinguishing agent and search and testing of alternatives is one of the most visible examples. Environmental considerations have also become more critical in post-crash fire hazards. These will be addressed during the symposium.

Further progress has been made in certification and testing methods and facilities and will be highlighted. This relates in particular to materials and structures. Aircraft structural design aspects in relation to fire safety will also be discussed. The AGARD Structures and Materials Panel has provided some of the papers in this area.

Aeromedical aspects will be discussed dealing primarily with toxicity of smoke and how to reduce their effect by selecting suitable materials. More insight will be provided in the causes of death in aircraft fire related accidents, for which different means of passenger and crew protection may be required. Some of the papers on this topic have been provided by the AGARD Aerospace Medical Panel. Passenger behaviour, including evacuation procedures will also be discussed during this symposium.

NATO and Nations will benefit from the high survivability of crews and aircraft as well as from overall cost reductions. Environmental impacts could be reduced by discussing the Halon replacement issue and industry will gain orientation for future developments in the military as well as the civil sector.

Thème

Ce symposium sur la sécurité incendie des aéronefs représente un point de rencontre unique où peuvent se rassembler toutes les différentes disciplines concernées et se développer des actions interdisciplinaires. Le symposium porte sur la sécurité incendie des aéronefs tant civils que militaires pour des sinistres se déclarant soit en vol, soit au sol à la suite d'un accident. Il traite également des caractéristiques des structures et matériaux se rapportant à la résistance au feu, de la toxicité des fumées, des mesures de protection pour les passagers et les équipages, ainsi que des comportements lors des évacuations d'urgence.

En 1989 le Panel PEP a organisé un symposium sur le même sujet qui a accueilli une nombreuse assistance. Depuis lors de nouveaux développements sont intervenus, dont l'interdiction du Halon en tant que produit d'extinction, et les études sur l'évaluation de produits de remplacement en sont l'un des exemples le plus frappant. Des considérations sur la protection de l'environnement ont aussi pris une nouvelle importance dans l'évaluation des risques des incendies se déclarant suite à un accident. Ces considérations seront abordées lors du symposium.

Les nouveaux progrès réalisés dans le domaine des méthodes et des installations d'homologation et d'essais seront détaillés. Les applications concernent en particulier les structures et les matériaux. La conception des structures aéronautiques par rapport à la sécurité incendie sera également discutée. Un certain nombre de communications sur ce sujet ont été fournies par le Panel AGARD des stuctures et matéraux.

Les aspects aéromédicaux seront examinés, notamment la toxicité des fumées et l'atténuation de leurs effets par un choix judicieux de matériaux. De nouvelles informations seront fournies sur les causes des décès lors des accidents suivis d'incendies, montrant qu'il faudra sans doute prévoir d'autres équipements d'autoprotection pour les passagers et les équipages. Un certain nombre de communications sur ce sujet ont été fournies par le Panel AGARD de médecine aérospatiale. Le comportement des passagers, entre autres vis à vis des procédures d'évacuation, sera également examiné lors du symposium.

Une meilleure capacité de survie des équipages et des aéronefs et la diminution globale des coûts que celle-ci implique, serait profitable aux pays membres de l'OTAN. L'impact de tels incendies sur l'environnement pourrait être atténué par le remplacement du Halon, ce qui donnerait aux industriels des orientations pour les développements futurs, tant dans le secteur militaire que civil.

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TECHNICAL EVALUATION REPORT

AGARD - Propulsion and Energetics Panel - 88th Symposium on Aircraft Fire Safety (Dresden, Germany, 14-17 October 1996)

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1. ABSTRACT

AGARD's Propulsion and Energetics Panel held its 88th Symposium on Aircraft Fire Safety in Dresden, Germany, from 14 to 17 October 1996.

The Symposium was intended as a platform for exchange and discussion on aircraft fire safety related issues, and for the assessment of on-going and needed research.

The program consisted of a Keynote Address and seven Sessions, with the presentation of thirty-three Papers from government organizations, industry, the military and the academic community. The presentations covered a broad range of issues, including accident experience, fire handling, on-board fire extinguishing and suppression systems, certification and testing, materials flammability, medical considerations, and passenger behaviour.

As evidenced by the presentations, major advances have been made in understanding, analysing and resolving fire-related problems since the previous Symposium on this subject some seven years ago. Significant progress was reported in a number of areas, particularly Halon replacement and water spray, fire and evacuation modeling, fuselage burnthrough, advanced fire-resistant materials, evacuation experimentation and

accident site health risk management.

The Symposium is considered to have been largely successful in achieving its objective of focussing on critical fire safety issues and research. It indicated the need to pursue or expand on-going programs, particularly in the areas of Halon replacement, fuselage burnthrough, fire and evacuation modeling, and passenger behaviour, and to implement further projects in specific areas, including training simulation and accident/incident data analysis.

The Symposium also emphasized the need for enhanced co-operation amongst all involved in the field of aircraft fire safety, particularly between the military and civil sectors.

2. INTRODUCTION

The objective of the Symposium was to provide a forum for the exchange and dissemination of knowledge, experience and expertise on aircraft fire safety, for the review of research carried out on the subject and, perhaps more importantly, for the identification and direction of future pertinent research.

The issue of aircraft fire safety is one that has generated significant interest since the early days of aviation. In more recent times, it has been a main area of concern, largely as a result of major accidents, both civil and military, where a number of fatalities were sustained as a result of both the fire itself, and the resultant toxic gases and smoke. Although fire-related accidents are relatively rare, when they do occur, there is often significant loss of life. Whilst there has been much progress in fire safety in recent years, efforts must continue to be made to further enhance occupant survivability.

The objectives in aircraft fire safety are to reduce the risk and extent of occurrence and, in the event of a fire, enhance occupant survivability through management of the threat and improvement of evacuation capability.

The technical program of the Symposium was opened with a Keynote Address which gave an overview of aircraft fire safety and relevant issues, and provided the context in which to consider the presentations and discussions .

The program was divided into seven distinct (though, inevitably, interrelated) Sessions, covering a wide spectrum of issues pertinent to aircraft fire safety:

I: Aircraft Fire Safety - General Overview / Addressing the significance of fire safety, and the value & limitations of accident data analysis.

II: Fires and Fire Handling / Reviewing the development of simulation and modeling, and accident site management.

III: On-Board Fire Extinguishing Systems / Addressing on-board fire detection, extinguishment and suppression, particularly Halon replacement and water spray.

IV: Certification and Testing / Reviewing a broad range of basic issues pertinent to testing and certification.

V: Materials and Structure Design for Fire Safety / Reviewing specific materials flammability issues, including burnthrough and advanced fire-resistant materials.

VI: Aeromedical Aspects Including Smoke Toxicity / Addressing the issue of toxicity from burning materials, and its effect and that of heat, on the human body.

VII: Passenger Protection and Behaviour / Reviewing evacuation experimentration, and evacuation simulation & modeling.

Predominating the presentations and discussions were the issues of Halon replacement (including water spray), fire and evacuation simulation and modeling, fuselage burnthrough, and advanced fire-resistant materials.

Each Session, and individual Papers therein, are reviewed separately. Comments are presented on the essence of each Session, and on the content of each Paper, the information presented by the speakers and, as appropriate, the significance of the associated discussions. (NOTE: Comments on individual Papers largely reflect their content as submitted prior to the Symposium.)

3. EVALUATION

Keynote Address

In his **Keynote Address**, C.P. Sarkos presented an overview of the significance of aircraft fire safety. He expanded on the differences between the two distinct safety issues which need to be considered, in-flight and post-crash fires, discussed past achievements, and presented a review of potential areas for future improvements. Mr. Sarkos further spoke of the importance of the lessons to be learned from accidents and incidents in defining future R & D activities, highlighting that there was ever increasing competition for a diminishing funding base (and a progressive reduction in the likely benefit-to-cost ratio of improvements). Mr. Sarkos put the issue of aircraft fire safety in perspective by suggesting it could be considered as one of management of fire, materials and people. Figure 1 refers.

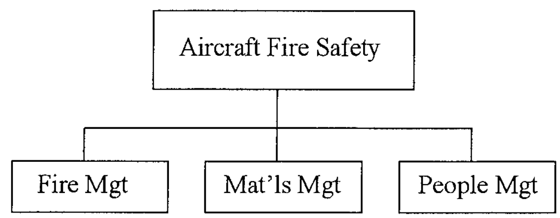

Figure 1 - Aircraft Fire Safety Management

Session I: Aircraft Fire Safety - General Overview

The Papers presented in this **Session** provided a realistic and revealing overview of the fire safety issues and challenges, most of which are common to both military and civil operations, that face designers, operators and responsible Authorities.

In particular, two of the presentations (Papers Nos. 2 and 3) provided thought-provoking views on the significant benefits to be gained from the analysis of data from past accidents.

The divergence in the findings of these Papers on the effectiveness of the safety improvements implemented in recent years requires consideration. Paper No. 2 draws its conclusions from a review of a number of accidents, whilst Paper No. 3 is based on an assessment of the findings from specific accidents. The difference between the conclusions of these Papers highlights the need for a rigorous and systematic approach to accident analysis, and for due consideration of the specifics of each accident case reviewed. Further, it indicates the need for a broadly coordinated review and assessment of the impact of safety improvements (past and projected).

Accident review and analysis is clearly a major means of directing the development of fire safety improvements. However it is suggested that it is also important to strive towards the development of tools and mechanisms that are not accident data dependent, and tools that will address safety deficiencies which have not yet resulted in accidents. The use of incident data may offer potential in this latter regard.

The Paper on fire/explosion protection of military transport aircraft (Paper No. 1) was of specific interest, particularly in that it presented technology, specifically OBIGGS, which could find application in civil aircraft, specifically transports. It is suggested that this needs to be explored. This Paper also provided a good overview of how, having identified the fire threat, specific research could be directed towards the creation of an optimal solution which is dependant on an aircraft's particular role as well as its design.

The model presented in Paper No. 4 was of special interest since it is capable of integrating accident and research data with user-defined scenarios. The development of simulation models, such as that described in the subject Paper (and those discussed in Papers Nos. 7 and 36, in Sessions II and VII respectively), illustrates the advances made in recent years in this field. Such models offer significant potential in the process of aircraft design for occupant fire protection, accident analysis, and evacuation certification of new aircraft. The most significant challenge now to be addressed is the establishment and implementation of validation mechanisms, particularly with regard to the use of evacuation models in demonstrating compliance with the (civil) evacuation certification requirements.

Paper No. 1 (E. Schwartz and S. Park) presented the major findings of a recent AGARD NATO study into the 'survivability' of military transport aircraft. The Paper focused on fire safety with particular emphasis on fuel system vulnerability. Consideration was given to several options for fuel tank protection against fire and explosion. It was concluded that a programme should be considered which would involve retrofitting a limited number of aircraft, involved in support missions to hostile areas, with flexible fuel tank foam and rigid dry bay foam. However, it was indicated that more extensive retrofit would benefit from the lighter weight solution offered by on-board inert gas Generation Systems (OBIGGS).

Paper No. 2 (A.F. Taylor) presented accident data which, it was suggested, indicates that survivability had shown no improvement over the last ten years. It was

suggested that more emphasis should be placed on minimizing the disbenefits of potential safety features in order to optimize the net benefit. The Paper stressed that care was needed in the examination of accident statistics in order to avoid distortions and to ensure that the wider implications of changes are not missed in an attempt to address specific problems. It was also indicated that accident analysis would be greatly enhanced if all accident investigating Authorities recorded the exact causes of death.

Paper No. 3 (R.G. Hill) presented a well-documented overview of some of the more significant fire-related accidents and major incidents since 1987. The presentation concentrated on a specific review of selected occurrences, with data demonstrating the effectiveness of fire safety improvements made in the period, together with an assessment of the areas having potential for future improvements. It was suggested that, while only small improvements were likely as a result of further cabin material flammability upgrades, improvements in occupant survivability could be achieved through enhanced flammability standards for 'hidden' materials. Improvements in oxygen, hydraulic and electrical systems, and enhancements in fuselage burnthrough resistance were also considered to have potential for enhancing occupant survivability. In this latter case, it was highlighted that cabin water spray systems showed significant potential, albeit that the cost-benefit analysis previously carried out was not favourable.

Paper No. 4 (P. Macey and M. Cordey-Hayes, with A.F. Taylor and W.G.B. Phillips) described a computer simulation model designed to allow analysis of aircraft accident scenarios and, specifically, the investigation of fire safety issues. It was reported that the model, which is still under development, attains its objectives by using risk analysis techniques to integrate real accident data and key research findings.

Session II: Fires and Fire Handling.

This **Session** addressed simulation and modeling (particularly computer-based) of fire development and extinguishment /suppression, including use in training, and the hazards associated with post-crash accident sites.

The Papers on fire modeling (Papers Nos. 5, 6 and 7) highlighted the advances made in the capabilities of numerical simulation of fire dynamics and extinguishment/ suppression. The model presented in Paper No. 7 was of particular interest in that it uses advanced Computational Fluid Dynamics (CFD) techniques to simultaneously resolve the pertinent equations of motion within computational cells, and integrates three-dimensional characterization of the process under study. However, it was stressed that mechanisms needed to be implemented to establish the validity of the models and confidence in the simulations.

It was noted, in the discussions, that there were fundamental differences of approach, and of assumptions, used in the construction of the different models. It is considered important that these issues be discussed further to gain an understanding of the relative merits of the different methodologies and, as appropriate, reach agreement on the basic premises, and on optimum methods to

be employed to attain the identified goals.

It is considered that models, such as those presented, offer significant potential for the review of actual and potential fire-related occurrences. Indeed, they are, at this time, probably the best (if not the only) means available to allow prediction of the fire characteristics of projected aircraft such as multi-deck very large transport aircraft prior to prototype construction. Again, the major issue is that of validation. It is accordingly considered that work on model development needs to be pursued, particularly in regard to validation and identification of models' limitations. A co-operative approach involving all interested parties is strongly urged, to enhance the achievement of optimal solutions.

It is unfortunate that only one Paper (Paper No. 10) was presented on the subject of computer-based training simulation, as it is considered that such tools offer significant potential in providing enhanced training capability, both for firefighting and for crew performance. Further work, specifically to assess the models' performance and limitations in this area, is recommended.

The Papers on post-crash hazards (Papers Nos. 8 and 9) clearly identified the health problems associated with accident sites, specifically where fire is involved, and discussed work being done to develop procedures to address these risks. It is considered that this is an area where further work is needed to further define the risks and appropriate means to address these, and where close co-operation between the military and civil Authorities would be of major benefit.

Paper No. 5 (G. Hadjisophocleous and Shu Cao) described work carried out in the modeling of aircraft cabin fire suppression using a water spray system. This work considered the extinguishment of a fuel fire using a water spray system at various mass flow rates. Determinations were made of heat release rates, water evaporation rates, and cabin ceiling temperatures for each mass flow rate. The Paper concluded that Computational Fluid Dynamics(CFD) models are an effective method for investigating fire suppression, and that a systematic study of all parameters involved would be necessary for the development of general design guidelines for fine water spray systems.

Paper No. 6 (H.G. Schrecker) described work done to study and simulate the characteristic phenomena of open tank fires, with particular reference to the heat transfer mechanism and 'boil-over' in burning oil-water systems.

This Paper was not available and hence no Technical Evaluation has been made.

Paper No. 7 (E. R. Galea and N. Hoffmann) presented the concept, design and basic parameters of a computer-based fire field model designed to predict the evolution, within an enclosure such as an aircraft cabin, of various fire parameters (e.g. temperature, velocities, pressures, smoke concentration), taking into consideration the interior configuration, fuselage openings (and wind conditions) and ventilation. The model's capability was illustrated by the presentation of simulations of typical aircraft accident fires. It was concluded that further work was

needed to upgrade the model, specifically with regard to fire spread, noting that present models largely rely on imposed fire descriptions, and with regard to inclusion of physical behaviour such as charring. It was indicated that the subject model has been designed so that it can be integrated within a 'total' evacuation model.

Paper No. 8 (G. Greene) presented an overview of the work being carried out within the UK Civil Aviation Authority to explore potential health hazards at aircraft accident sites. It reported that the UK Health and Safety Executive has been working on generating a list of hazardous materials likely to be present at an accident site, and their hazard potential to personnel on the site. Particular attention has been directed towards composite materials, in relation to the effects of microscopic particles and toxic gases that may be released following a post-crash fire. It was indicated that future studies in this field are intended to include fibre release and debris spread at accident sites.

Paper No. 9 (J.W.T. Andrews) presented the experience of the RAF in the problems encountered at post-crash accident sites, particularly from shattered and burned carbon composites, and the procedures that have been put in place to protect personnel from hazardous substances, and substances that might become hazardous the event of fire, at an accident site. The Paper concluded by stressing the need for co-operation between all concerned parties (including manufacturers, operators, and Authorities) in identifying the hazards to personnel at accident sites, and in developing standards and mechanisms to reduce/minimize these risks.

Paper No. 10 (S.H. Merchant and R.M. Bradner) described the simulator developed by their company to train personnel in firefighting, based on the military concept of Command, Control, Communication, Computer and Information (C^4I). The Simulator is claimed to be the first of its kind for training personnel to meet the civilian emergency training requirements.

Session III: On-board Fire Extinguishing Systems

This **Session** addressed various issues relevant to fire suppression and extinguishing on board aircraft, including a fire safety concept for military combat aircraft (Paper No.11), water spray (Paper No. 12) and Halon replacement (Papers Nos. 13, 14, 15 and 16).

The latter subject largely predominated the Session, with general agreement on the complexity of the issue and on the need to maintain the level of safety established by Halons. It was stressed that, in addition to replacement agent/system extinguishing/ suppression performance, due consideration needed to be given to human/toxicity issues, and to environmental constraints, both present and future. It was further noted that, in most States, the current ban only addresses Halon production, but that many States are considering a total ban on Halon use in the future. Considering the evolution of environmental legislations towards Halon banning, and dwindling Halon availability, it is considered that work on the subject, specifically in regard to the development of certification criteria and of replacement agents/systems (including water spray) needs

to be pursued with a high degree of priority. Further, it is recommended that potentially viable replacement agents/systems (such as Triodide[tm]) should be the object of priority testing and evaluation.

Although the work presented in Paper No. 11 was specifically directed at combat aircraft, the principles and expertise developed with respect to fire detection and suppression/ extinguishment activation are considered to have applications to other aircraft including transport aircraft, both military and civil. It is recommended that such application be explored.

Paper No. 11 (C. Manthey) described the mechanisms for the development of fires and explosions in combat aircraft fuel tanks and dry bays as a result of penetration by munitions. The use of optical sensors for the detection of fires or explosions, and subsequent suppression activation, was considered to be the most practicable means available due to the requirement for short system response time. Also discussed were the characteristics of various extinguishants and the use of Ultra Violet Flame Sensors on military aircraft engines.

Paper No. 12 (R.G. Hill, T.R. Marker and C.P. Sarkos) presented the details of a full-scale fire test program, implemented by the civil aviation Authority of the US, jointly with those of the UK and Canada, to evaluate and optimize on-board water spray systems for two specific applications: to combat cabin fires from post-crash external fuel-fed fires and to suppress in-flight cargo fires. Results of the tests indicated that a cabin system can (with small amounts of water) significantly increase survival time by delaying the onset of flashover, reducing cabin temperature and removing water-soluble gases, and that an optimized cargo compartment system can effectively control/suppress a deep-seated in-flight fire for extended periods of time. It was concluded that the cost/benefit ratio for cabin systems, which was initially unfavourable, may now become favourable in combination with cargo systems if the latter are implemented as a result of the need to replace of Halons.

Paper No. 13 (W. Rudolph and M. Rieland) presented a brief historical overview of the evolution of Halons, followed by an explanation of the 'fire tetrahedron' postulate to describe the molecular process of combustion, thereby forming a basis for the determination of the performance of Halon replacement agents.

Paper No. 14 (K.M. Kallergis) reported on experiments conducted to assess the performance of three agents against Halon 1211 in hand-held extinguishers. The work involved two activities: combating seat and carpet fires in a full-scale cabin mock-ups (using gasoline to 'accelerate' the fire, thus simulating a terrorist act), and performance testing (flame extinguishment) in a hidden-fire test mock-up. The results showed a wide range of extinguishing effectiveness, with only CF_3I achieving performance comparable with that of Halon 1211, although presenting higher toxicity characteristics. The Paper concluded by stating that other factors, such as environmental, human and toxicological, also needed to be considered in assessing various agents for different applications.

Paper No. 15 (N.J. Povey) presented an overview of the issues and problems relative

to Halon replacement, and expanded on the specifics of a program of work by the civil aviation Authorities to develop appropriate minimum performance criteria for the certification of hand-held Halon-replacement extinguishers, to fight hidden fires. The test procedure developed was aimed at achieving an extinguishing performance equivalent to that of Halon 1211, using a test chamber designed to replicate the volumes, airflows and physical restrictions typical of a fuselage's hidden areas. The presentation highlighted the effectiveness of the development process used in this program, indicating that a similar process is being followed in Halon replacement projects relating to other areas of the aircraft, including engines and cargo compartments.

Paper No. 16 (R.G. Hill and C.P. Sarkos) presented an overview of the Halon replacement issues facing civil aviation, and discussed the specifics of a program of work being conducted by the civil aviation Authorities of the US, Europe and Canada, and involving the participation of industry. It was explained that the basic objective of the Program was the development of certification criteria for the approval of non-Halon agents/systems, and that the goal was the achievement of fire extinguishing/ suppression performance equivalent to that of Halons. It was explained that the program considered four applications: cargo compartments, engines and auxiliary power units, hand-held extinguishers and lavatory trash receptacles, and that it involved the development of full-scale test articles, the conduct of full-scale evaluation tests, and the development of minimum acceptable performance levels, standard performance tests and certification acceptance criteria.

Session IV: Certification and Testing

The Papers presented in this **Session** addressed a broad range of issues relevant to testing and certification. Specifically, the Papers reviewed research in the performance of firefighting powders (Paper No. 17), the development of a burner test standard for engine nacelle components (Paper No.21), combustor burnthrough testing (Paper No. 22), and basic considerations pertinent to military transport aircraft fire safety certification (Paper No. 20).

The above are considered important inasmuch as they are fundamental in the establishment of viable common processes and procedures for testing and certification, within the context of advancing technology.

Of particular interest was Paper No. 22, which addressed progress made towards the establishment of test set-ups and procedures to assess the performance of combustor burnthrough shields. Work needs to be implemented to further quantify pertinent parameters, and further work should be implemented to develop viable test procedures/criteria.

Paper No. 17 (E. Brogan) presented the results of dry powder fire extinguisher tests (small & large scale) aimed at designing a test to specifically assess the performance of extinguishers in airport fuel fire applications. The tests utilized Monnex's performance as the benchmark for the evaluation of other agents, and were carried out using fire trays and a medium-scale instrumented (thermocouples and heat flux radiometers) test article designed to be representative of a

running/cascading fuel fire and a spray fire.

***Paper No. 18** (E. Antonatus) was not presented.*

***Paper No. 19** (A. Tewarson) was not presented.*

Paper No. 20 (B. Marques and E. Nin) described the certification process adopted in Spain for military aircraft. Also described were the factors considered in evaluating potential fire hazards, retention of cargo, accessibility of exits, suitability of materials in terms of combustion, smoke and toxic gas release, and the circumstances under which aircraft modifications are required.

Paper No. 21 (P.R. Derouet and J.Y. Picart) described the work and results of tests conducted to develop procedures and equipment for the testing of components installed in engine nacelle fire-designated zones. The intent was to establish test parameters for a propane burner which would produce results that are thermally equivalent to those using a fuel burner.

Paper No. 22 (N.L. Messersmith and S.N.B. Murthy) described the current status of work to establish the basis for a preliminary design of a test facility and testing procedure for fire shield materials intended for the protection of engine and aircraft components from jets resulting from combustor burnthrough. The project comprised three phases: 1) to determine the characteristics of the mechanical and thermal loads that a plate may be subjected to due to impingement by a jet; 2) to address the complexities in the loads for varying impact plate geometries; and 3) to develop a test facility and acceptable test procedure. Phase 1) is complete, and plate loading (mechanical and thermal) and jet structure have been derived.

Session V: Materials and Structure Design for Fire Safety

This **Session** addressed some of the significant advances made in fire-resistant materials (Papers Nos. 26 and 27), design considerations for fire protection of aircraft and engines (Papers No. 23 and 25), and the work being carried out to develop test standards to improve the burnthrough resistance of aircraft fuselages (Paper No. 24).

Based on the data presented, advanced fire-resistant materials would seem to offer great potential for improving the fire hardening of both aircraft structures and cabin interiors. It is recommended that this work be pursued.

Papers Nos. 23 and 25 are of particular value to the aircraft and engine manufacturers in terms of the design considerations that should be given to the strength of aircraft structures exposed to fire, and the precautions to be taken with the use of titanium in engines.

The collaborative work carried out to date by the civil aviation Authorities towards enhancing the burnthrough resistance of fuselages is considered an extremely valuable step towards improved occupant survivability in accidents involving large external fuel fires. This needs to be pursued with significant priority. Additionally, and further to this work, it is recommended that identified potentially viable improvements be assessed and that due consideration be given

to early implementation.

Paper No. 23 (M. Voglsinger, R. Lang, G. Günther and J. Wördehoff) described the potential problems that may be encountered in assessing the structural integrity of aircraft structures following their subjection to fire. The nature of the threat, structural design requirements, damage evaluation, and preventative measures for metallic and composite materials were all discussed.

Paper No. 24 (T.R. Marker, D.C. Dodd and N.J. Povey) presented the details of a program jointly undertaken by the civil aviation Authorities of the US and the UK to evaluate and improve the fuselage burnthrough resistance of transport category airplanes to large external fuel fires. Preliminary work on the subject consisted of a series of tests using surplus aircraft, which indicated that the aluminium skin provides 30 to 60 seconds of protection from fire penetration, and that the performance of thermal-acoustical insulation is a significant factor in preventing flame penetration. The next phase of the program consisted of the development of a medium-scale test device for carrying out investigative (and possibly, eventually, certification) work, and the development of a full-scale fire test article for comparative tests. This was followed by a series of performance tests which established that the results obtained with the medium-scale test device were basically consistent with those of the full-scale test article. It was reported that the follow-on phase of the program will consist of research aimed at identifying and developing materials and processes which will improve burnthrough.

Paper No. 25 (T. Uihlein and H. Schlegel) described the characteristics and potential consequences of titanium fires within an engine. The properties of titanium, the factors affecting ignition, the measures that may be taken to avoid or protect against titanium fires, and the value of rig testing were all discussed.

Paper No. 26 (G.H.J.J Roebroeks) described the properties of GLARE®,which consists of thin aluminium sheets bonded with epoxy adhesive layers containing high strength glass fibres. Based on the testing presented,it is claimed that this material is superior to monolithic aluminium in many ways particularly with respect to fire resistance, corrosion, fatigue damage, impact strength, weight, reparability and thermal insulation. It was reported that in-service evaluation is currently being carried out on several aircraft types.

Paper No. 27 (R.. Lyon, U. Sorathia, P.N. Balaguru & A. Foden, and J. Davidovits & M. Davidovics) described the fire-resisting characteristics and potential use of Geopolymers in aircraft cabin interiors. The composition and preparation of test specimens on materials currently used in aircraft cabin interiors, and Geopolymers were also outlined and the test methods and results described. Geopolymers, although inferior to structural steel in terms of flexural strength, modulus, and cost were stated to be non-combustible, non-toxic, and non-corrosive.

Session VI: Aeromedical Aspects Including Smoke Toxicity

The Papers in this **Session** concentrated on issues and problems associated with the

effect of fire and of combustion by-products on humans. Specifically, the Papers described the research carried out to investigate the toxicity hazards created by burning materials (Papers Nos. 28 and 31), and the work undertaken to develop means for determining the levels at which incapacitation occurs (Paper No. 33). The methods being developed to identify and quantify the toxicants levels present in humans as a result of exposure to smoke and combustion gases were also described. Presentations were made on the effect of fire on the human body and on the need to accurately determine the causes of death (Paper No. 30), and on the use of modeling to predict the extent of burns likely to be incurred under varying heat and fire threats (Paper No.32).

The issues and problems raised are certainly most challenging. It is considered that these are issues for which further work is needed, specifically in regard to assessment of human tolerance. Further, accident investigating Authorities should be urged to implement the mechanisms necessary to make accurate determinations of causes of death in accidents

Paper No. 28 (A. Mansuet and J.-F. Petit) reported on work aimed at determining whether incapacitation could be linked to a readily measurable characteristic of material degradation under fire. The experiments, which involved exposing animal subjects (mice) to the combustion products of typical cabin materials in the 'mini corner test' device, showed a relationship between sample mass loss and incapacitation.

***Paper No. 29** (T.I. Eklund) was not presented.*

Paper No. 30 (I.R. Hill) discussed some of the difficulties that are encountered in accurately diagnosing cause of death in fire accidents. The reactions of the human body to high temperature environments and fire were described, and the possibilities for incorrect diagnosis of cause of death discussed. The importance of accurate determinations of causes of death was emphasised, to ensure that the correct safety remedial actions are taken.

Paper No. 31 (C.R. Miller) described work carried out to investigate the toxicity of combustion products of advanced composite materials. The work involved the investigation of the differing effects of toxic gases on rodents, and a consideration of measures of toxicity.

This Paper was not available and hence no Technical Evaluation has been made.

Paper No. 32 (F.S. Knox III and B. Billotte) described the computer model BURNSIM, which may be used to predict the potential burn hazard to human beings subjected to heat sources. An outline of some of its applications and the background, structure, and validation of the model was also given.

Paper No. 33 (H. Krause) described the work carried out by the German Air Force Institute of Aerospace Medicine into the detection and identification of toxic substances which may be present in the blood and urine samples of aircraft occupants subjected to in-flight or post-crash fires. The new analytical techniques developed by the Institute are showing very good results in terms of separation performance, sensitivity

and identification of substances.

Session VII: Passenger Protection and Behaviour

This **Session** addressed issues related to the human aspects of emergency evacuation. Paper No. 35 presented the results of work to determine the influence of various factors on the behaviour and performance of passengers, while Papers Nos. 34 and 36 concentrated on the use of computer modeling to simulate these.

Considering the criticality of the issue, and the extent of concerns and work on the subject, it is somewhat surprising and unfortunate that there were only three Papers presented in this area, with only one specific Paper on evacuation experimentation.

The type of work presented by Paper No. 35 is considered to hold significant potential in leading to improvements in survivability. Much progress has been made in recent years in evacuation research, but there are a number of issues which remain to be addressed. Further work to assess human behaviour and performance in various scenarios, conditions and different cabin configurations, should be strongly supported and needs to be pursued with significant priority, not only because it is essential to the development of improved cabin designs and evacuation criteria, but also because it provides needed data to support model development and validation.

This notwithstanding, it is suggested that an enhanced measure of psychological characterization should be incorporated in human behaviour research. This, in addition to improving understanding of the findings, should provide valuable data for the models' development.

In parallel with the above, work needs to be pursued to develop the models (such as those presented in Papers Nos. 34 and 36) to a level where they will become useful and reliable tools to simulate human behaviour and performance. In particular, work should be undertaken to further enhance the models' development towards use in evacuation certification, and a project to review and assess models' capabilities and limitations in this application should be implemented.

Paper No. 34 (M.C. Court and J.H. Marcus) described the use of object-orientated programming in the simulation of human behaviour in an emergency evacuation. The development of a validated model is considered to be of considerable value, both in terms of its potential ability to replace the current evacuation testing required of the manufacturer as part of an aircraft's certification programme, and its use in understanding the significance of various cabin configurations and fire scenarios. The model under development is currently being validated against existing certification data and the study is also in the process of identifying the physical and psychological parameters most influential to occupant survival.

Paper No. 35 (H.C. Muir and A. Cobbett) discussed the 'human' factors which influence survival in aircraft accidents, and presented the results of experiments conducted to explore the influence of cabin crew presence and behaviour on the evacuation of passengers in an emergency.

The evacuations were carried out by volunteers from the general public in a 'narrow-body' aircraft simulator, with the appropriate urgency being simulated through bonus payments designed to generate behaviour typical of that observed in some accidents. The work indicated the viability of the motivational techniques used. The results obtained suggested that the number, actions and behaviour of cabin attendants significantly influenced the speed at which passengers were able to evacuate. Particularly, it was determined that assertive behaviour played a significant role in the achievement of rapid evacuation.

Paper No. 36 (E.R. Galea, M. Owen and P. Lawrence) described work currently being carried out into the development of the evacuation model air-EXODUS, and the database containing information from aircraft accident survivors AASK. A detailed account was given of the characteristics and capabilities of the model and the factual data, based on actual accident survivor reports contained in AASK. The use of certification and experimental trials data in support of the model, and its success in predicting trials results were also described. The Paper concluded that the model was currently capable of use as a design tool for new aircraft configurations, as an aid to the development of cabin crew procedures/ training, as an analytical tool in the investigation of accidents and, when validated, offer an alternative to full-scale certification demonstrations.

***Paper No.** 37 (P. Glyn-Davies) was not presented.*

4. CONCLUSIONS

The Symposium provided an opportunity for fire safety specialists to address a broad range of fire safety related issues, discuss recent progress in research and identify future needed pertinent activities.

The work reported indicates that significant progress has been made in many key aspects of aircraft fire safety, more particularly in:

- On-board fire extinguishing/suppression agents and systems, specifically Halon replacement, including water spray systems for cargo compartments (and cabins).

- Advanced fire-resistant materials, and work towards improvement of fuselage burnthrough resistance.

- Computer modeling and simulation of fire/extinguishment evolution and of passenger evacuation.

- Effects of toxicants and heat/fire on humans.

- Management of health hazards at accident sites, specifically in cases involving fire.

However, coupled with such progress, is the continuing evolution of aviation which, in itself, raises new challenges, such as the fire vulnerability of extended upper decks on large transport airplanes, and the evacuation of large numbers of occupants from very large and multi-aisle aircraft.

The Symposium is considered to have been successful in achieving its objectives of providing for the exchange and dissemination

of knowledge, experience and expertise on aircraft fire safety, and for the identification of needed research. It indicated the need to pursue or expand on a number of key on-going programs, particularly in the areas of Halon replacement, fuselage burnthrough resistance, fire modeling, and passenger behaviour and evacuation modeling (including evacuation certification), and to implement further projects in specific areas, including accident/incident data analysis, human tolerance to fire/heat, and training simulation. (Section 5, Recommendations, refers.)

Also, particularly, the Symposium strongly emphasized the need for enhance cooperation amongst all involved in the field of aircraft fire safety, Authorities, manufacturers and operators, and particularly between the military and civil sectors. It is considered that the latter is an area in which AGARD could play a key role

Although aircraft fire safety is already very high, accidents involving fire-related fatalities and injuries continue to occur. The challenge must be to reduce these further, through a rational, systematic and balanced approach to all potentially viable solutions.

5. RECOMMENDATIONS

Technical

A broad spectrum of issues, problems and concerns have been discussed in this Symposium. Specific recommendations have been discussed in the body of this Report. The main points, and additional considerations, are presented below:

- Extensive work has been carried out in the area of Halon replacement, with regard to the development of performance standards and test criteria, and the development and assessment of agents and systems. Current environmental trends, including possible banning on use, dictate that this work needs to be widely endorsed and pursued with a high degree of priority. Concurently, it is recommended that evaluation of potentially viable agents/systems (such as Triodide(tm)) be accelerated.

  Of specific interest on the subject is the potential of water spray as a Halon replacement, particularly for cargo compartment fire suppression. Cabin water spray systems have been shown to be effective in significantly extending survival time, but were initially assessed not to be cost effective. Considering their potential to be effective for cargo compartment fire suppression, the development of water spray systems needs to be pursued for this application, particularly considering that the use of water sprays in this role could lead to combined cargo compartment and cabin systems which would likely present a positive benefit-to-cost ratio to the latter.

- Advances made in the development of fire-resistant materials, and the work presently underway to improve burnthrough resistance of fuselages offer significant potential in improving aircraft fire safety, specifically in cases of larger external fuel fires. These are considered to be extremely worthy and promising

efforts which need to be pursued.

Particularly, it is recommended that the current co-operative research work being carried out by the civil aviation Authorities be pursued with significant priority and that, concurently, aviation authorities review and assess identified potentially viable improvements for early implementation.

- Fire and evacuation modeling has dramatically progressed in recent years, as evidenced by the number and extent of presentations and discussions on the subject. Modeling holds significant potential to predict fire evolution and extinguishment/suppression, and occupant evacuation in a wide range of scenarios. Particularly, it is considered to have special relevance to future/novel aircraft designs, such as very large transports, by allowing assessment of the aircraft's fire and evacuation characteristics at the early concept/design stages. It is accordingly recommended that work on model development be pursued with priority, specifically in regard to validation and identification of models' limitations. Special emphasis should be placed on assessing models' capabilities and identifying their limitations for use in (civil) evacuation certification, together with a co-ordinated assessment of the basic premises and approaches used. A study in this regard is recommended.

This notwithstanding, the implementation of work to assess the performance and limitations of models in training simulation is recommended.

Considering the broad range of issues requiring consideration, it is suggested that a Symposium dedicated to modeling would be most beneficial.

- Although improvements in fire and materials management (prevention, detection, extinguishment/ suppression and hardening) have significantly enhanced occupant survivability in recent years, they cannot assure total fire safety. Effective and rapid evacuation (people management), must also be a prime objective. Knowledge and understanding of passenger behaviour under various conditions is key to the achievement of this objective.

The factors relating to successful occupant evacuation are critical to survivability in aircraft accidents involving fire. Over recent years, a broad base of knowledge has been acquired on the factors that affect the success of emergency evacuations, but there is a need to assess these much more extensively and under a much broader range of conditions. Issues requiring consideration include, amongst others, pre-flight briefing, evacuation decision-making, crew performance and training, configurational aspects, and experimental protocols. This is of particular interest and significance in regard to the (civil) requirements for the demonstration of the evacuation capability of transport category airplanes.

It is recommended that research on the subject should be significantly expanded, particularly in co-ordination with

modeling work, and pursued with priority. It is also suggested that enhanced characterization of psychological factors should be incorporated in all such research.

Also, it is suggested that a Symposium should be held on the subject to foster the advancement of knowledge, research and co-operation.

- Accident and incident data analysis is considered fundamental to an understanding of the critical factors influencing accident prevention and occupant survivability, and in the identification of needed research and likely potential of safety improvements.

  The Papers presented, and the associated discussions, emphasized the need for caution and rigor in approach when forming conclusions from accident/incident data. Improvements are recommended both in terms of data availability and analytical tools and methods used.

  In this regard, it is suggested that co-ordinated efforts should be made to put in place an extensive readily-accessible database of accident and incident information pertinent to occupant survivability, including fire and evacuation data.This notwithstanding, it is suggested that a project be implemented to perform a broad coordinated review and of the impact of safety improvements (past and projected).

  Currently, the exchange of information between the military and civil sectors in regard to accident/incident data is limited. Improvements in data exchange and on the lessons learned from experience would prove beneficial to all. It is recommended that mechanisms should be put in place to achieve this exchange. It is suggested that AGARD could effectively coordinate such a program

- The usefulness of accident analysis (broad or specific) in identifying and focusing needed fire safety research, and the capability to properly address safety deficiencies, can only be achieved if the causes of death and injury severity are accurately identified. It is recommended that all accident investigating Authorities be urged to put in place the approriate mechanisms to make such determinations.

- Notwithstanding the usefulness of accident data analysis, it is suggested that efforts should also be directed at developing other mechanisms to identify needed research and areas of potential improvement. In this regard, it is recommended that projects be implemented to develop tools that are not strictly accident data dependent, and tools that will allow identification of safety deficiencies that have not yet resulted in accidents.

- Extremely valuable work has been done on the issue of combustor burnthrough. Progress in this area holds significant potential in improving fire safety. It is suggested that work should be pursued to further quantify the pertinent parameters, and that work should be initiated to

develop appropriate qualification test standards and criteria.

- Emergency procedures are also considered an essential aspect of fire survival. Whilst firefighting training was the subject of one Paper at this Symposium, flight and cabin crew training and procedures were unfortunately only addressed to a very limited degree. It is suggested that the issues relating to emergency crew drills should be included in future Symposiums.

- Significant work has been done to assess and quantify the effects of fire/heat and of smoke/toxic gases on humans. It is suggested that further research needs to be implemented in this area, particularly in regard to human tolerance to heat, together with work aimed at modeling these effects.

- Significant work and progress has been made in the identification, assessment and management of post-crash hazards at accident sites. It is recommended that work should be pursued in this regard, with particular emphasis on the risks associated with fire occurences. Co-operation amongst all concerned, specifically the military and civil sectors is deemed particularly desirable in this activity.

- It is noted that a large portion of the work reported in this Symposium deals with fire safety in transport airplanes. Although these aircraft offer the most important challenge and potential global benefits due to their large passenger capacity, it should be recognized that other types of aircraft, including rotorcraft and lower-weight category airplanes (both civil and military), present specific fire safety problems which need to be addressed.

- The technology of on-board inert gas generation systems (OBIGGS), developed for fuel tank inerting on military aircraft, may have application to civil aircraft, particularly transports. It is recommended that a work program be implemented to review the viability of this technology on civil aircraft and, as appropriate, to establish the best means of achieving this.

- A number of other areas/issues should also be the object of continued or further research (athough, in some instances, being addressed in existing programs). These include, amongst others, fire and smoke detection, hidden fires, lavatory fires, and aircraft systems' fire resistance.

It is considered essential that increased emphasis be placed on enhanced co-operation and exchange amongst all involved in the field of aircraft fire safety, in particular between the civil and military sectors. It is suggested that the latter is an area in which AGARD could act as an effective catalyst.

Administrative

- Due to the rapid advancement of fire safety technology, and the extent of research underway and planned, AGARD PEP Aircraft Fire Safety Symposiums should be held at a maximum of five year intervals,

preferably three to four.

- The Symposium would benefit from increased question/discussion time after each presentation. An open forum at the end of each Session would also likely to prove of benefit in promoting discussion on the key issues and in focusing on the way forward in research.

- To enhance Symposium effectiveness, it is suggested that all Papers should be made available at the beginning of the Symposium. This would give the participants the opportunity to review the material prior to presentation, thereby allowing more productive discussions.

- It was noted that there was a broad spectrum of depth, and significant variance in presentation, between the various Papers, and that some were relatively general in nature while others were very specific. It is suggested that, as much as possible, efforts should be made to enhance uniformity in content level.

This completes the Technical Evaluation. It now behoves all to pursue the development and implementation of aircraft fire safety improvements through their respective organizations.

Statement by Mr. Constantine P. Sarkos

Following the Symposium the Keynote Speaker, Mr. Constantine P. Sarkos, Manager of the Fire Safety Section at the Federal Aviation Administration William J. Hughes Technical Center, sent comments to AGARD which are reproduced hereunder. It is felt that his text should be included as it states the desirable improvements to fire safety as seen from a major civil aviation authority.

"The Aircraft Fire Safety Symposium should be convened more frequently than in the past, preferably every 4 years.

Military OBIGGS* technology needs to be transferred to civil commercial transport applications relative to oxygen system safety and fuel tank inerting.

A directed study is needed to examine commercial transport world-wide accident experience to determine the impact of regulatory improvements that were products of R&D programs.

An in-depth analysis of recent aircraft fire accidents/incidents is required to identify fruitful R&D activities (with estimates of potential benefits in terms of reduced fatalities and aircraft losses).

An objective analysis should be made of the applicability and limitations of computer cabin fire models as a replacement or supplement to full-scale fire tests and as a training tool for cabin crew members.

R&D activities related to the development and evaluation of halon replacement agents/systems must receive adequate funding and high priority because of the dwindling supply of halons and the real possibility of halon systems decommissioning and halon destruction for environmental reasons.

The halon replacement agent triodid, a "drop-in" agent, should receive priority evaluation in engine nacelle applications in terms of effectiveness, material compatibility and worker exposure following accidental discharge.

A standard burner can burnthrough test methodology needs to be developed.

The regulatory authorities should consider the implementation of fuselage burnthrough resistance technology demonstrated by the joint FAA/CAA R&D program.

Accident investigation organizations must strive or acquire the capability to differentiate between fatalities caused by trauma, heat/flame and toxic gases.

An in-depth study is needed to define human tolerance to elevated temperatures relative to aircraft postcrash fire survivability.

The suitability of computer evacuation models as replacement/supplement to the evacuation demonstration requirement should be determined.

Research employing human subjects to improve aircraft emergency evacuations should continue to be supported.

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* On-Board Inert Gas Generation Systems

A REVIEW OF PROGRESS AND FUTURE TRENDS IN AIRCRAFT FIRE SAFETY R&D

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1. SUMMARY

This keynote address will differentiate between in-flight and postcrash fire safety, outline the general approach for improvements and review past R&D regulatory products. A synopsis will be given of the subject matter that will be covered during this AGARD meeting. Future research considerations will also be described.

2. AIRCRAFT FIRE SAFETY

Aircraft fire safety entails two distinct fire protection activities - in-flight fire safety and postcrash fire survivability. The general goals for each activity are far different from one another because the fire threats and periods of protection are dissimilar.

In commercial transport aircraft, the in-flight fire problem is a hidden fire that occurs in an inaccessible location (e.g., cargo compartment) or that is difficult to locate (e.g., lavatory area). The primary design goal is to minimize the likelihood of a fire to begin with at any location throughout the aircraft. However, if a fire should occur, the goal is to reliably detect the fire and to extinguish or suppress the fire until the aircraft can be safely landed, which may take as long as 3 hours during transoceanic flights. Since deep-seated cargo fires cannot be readily extinguished, suppression of this type of fire also requires adequate protection of critical flight systems and aircraft occupants. In military aircraft, there is an additional requirement for fire/explosion protection against gunfire.

In the United States, transport cabin fire and smoke incidents are not infrequent, but are quickly extinguished or rectified by the crew. The most common cabin fire/smoke sources occur in the gallery or because of lighting ballast problems. However, fatal hidden in-flight fires are rare events of great consequence. The recent ValuJet DC-9 in-flight fire (May 11, 1996, Florida Everglades) claimed the lives of the 110 aircraft occupants. However, the previous fatal in-flight fire involving a US airliner (all passenger aircraft) occurred over 30 years ago (United Viscount 745D, July 9, 1964, Parrottsville, Tennessee).

Unlike the long period of protection required for deep-seated in-flight fires, enhancements in postcrash fire survivability are dictated by the time necessary for the complete evacuation of passengers. In an actual accident, the evacuation may take as little as less than one minute, but certainly no more than 5 minutes, depending on a number of factors associated with the accident conditions, passengers and aircraft design, including passenger loading (percentage of seats occupied), passenger mix, availability of exits, obstruction of exit pathways, severity of fire and smoke conditions, etc. This real evacuation time is sometimes confused with the 90-second evacuation requirement imposed by the regulatory authorities to demonstrate evacuation capabilities under specified conditions.

Postcrash fires are, of course, far more intense than typical in-flight fires. In most cases, the fire originates upon the ignition of large quantities of jet fuel spilled from ruptured wing tanks. The main concern is the spread of the fire into the aircraft and the effect of burning interior materials on passenger evacuation and the creation of untenable conditions. The primary design goals for enhanced postcrash fire survivability are twofold: additional available time for passengers to escape and increased passenger evacuation rate.

Fatal postcrash fires involving commercial airliners occur far more frequently than their in-flight counterparts. On an absolute scale, however, fatal, postcrash fires are also relatively rare events. The incidence of U.S. airliners involved in fatal crash fires averages approximately one event per year.

3. IMPROVEMENTS IN AIRCRAFT FIRE SAFETY

Opportunities for improvements in aircraft safety are offered by three basic pathways: fire management, materials management and people management.

Fire management consists of active fire detection and extinguishment/suppression systems and/or operational procedures designed to extinguish, control or minimize the effects of a fire. As defined here, fire management systems and procedures in commercial transports have been employed for in-flight fire safety only.

Materials management refers to the selection of materials to minimize burning hazards or to perform a fire protection function. An example of the former are seat cushions designed to reduce or prevent burning of the urethane foam padding and limit surface flame spread. Burnthrough resistant cargo liners designed to prevent the spread of cargo fires outside the cargo compartment illustrate the latter. Materials selection is based on standard small-scale fire test criteria. Critical to the effectiveness of this approach is the development of small-scale test methods that correlate with real fire (full-scale fire test) behavior. Also very important is the relationship between pass/fail criteria and benefit (e.g., enhanced survivability, burn-

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

through resistance, etc.). Materials selection is a passive fire protection approach because of the built-in and non-active nature of this approach.

People management consists of measures to reduce or protect aircraft passengers and crewmembers against the effects of fire. For example, floor proximity lighting is designed to increase passenger evacuation rates, thereby reducing fire hazard exposure, when overhead lights are obscured by smoke accumulation during a postcrash fire. Similarly, protective breathing equipment is provided for protection of crewmembers during in-flight firefighting. Obviously, the role of crewmembers in efforts to manage the movement of passengers is critical, as is the associated crewmember training. Also, the life threatening and "once-in-a-lifetime" nature of an aircraft fire dictates that passenger escape activities be simple and straightforward in order to avoid confusion and possible costly delays in evacuation.

Beginning in the mid-1980's, an unprecedented series of fire safety regulations were adopted by the regulatory authorities (Sarkos, 1989). The majority of the regulations were products of research conducted by the Federal Aviation Administration (FAA) and were aimed at improving survivability during postcrash fires and preventing uncontrollable in-flight fires. The following is a summary of the regulations.

Postcrash Fire

Seat Cushion Fire Blocking Layers. This rule requires that seat cushions meet a severe flammability test that simulates a postcrash fire. The standard reduces the burning rate and involvement of the flammable (albeit fire retardant) urethane foam during a severe cabin fire. Most US airlines encapsulate the urethane foam with a highly fire resistant fire blocking layer material.

Low Heat/Smoke Release Panels. This rule requires that large surface area panels (sidewalls, ceiling, stowage bins and partitions) meet a stringent heat release test. Airframe manufacturers were required to develop new material designs in order to gain compliance with the standard. In this sense, the standard was a technology driver.

Floor Proximity Lighting. This rule requires that airplane emergency lighting systems provide escape path (aisle) definition and identify each exit when smoke accumulates in the upper cabin and obscures overhead lights.

Radiant Heat Resistant Slides. This revised Technical Standard Order (TSO) includes a new test requirement that measures the heat resistance of pressurized slide material. Evacuation slides constructed of reflective materials compliant with this test remain inflated much longer when subjected to fuel fire radiative heating during an emergency evacuation.

Exit Row Seating. This rule requires that persons seated next to emergency exits must have the physical and mental capability to operate the exit and possibly assist other passengers in emergency evacuations.

Location of Passenger Emergency Exits. This rule improves passenger evacuation in an emergency by limiting the distance between adjacent emergency exits on transport airplanes to 60 feet.

Accessibility of Overwing Type III Exits. This rule improves passenger evacuation in an emergency by improving access or passageways to overwing Type III exits (hatches)

In-Flight Fire.

Halon 1211 Extinguishers. This rule requires at least two Halon 1211 hand-held extinguishers in every transport airplane. The requirement was based on the demonstrated superior fire knockdown capabilities and low toxicity of Halon 1211.

Lavatory Fire Protection. This rule requires lavatory smoke detectors and lavatory waste receptacles outfitted with a built-in fire extinguisher.

Burnthrough Resistance Cargo Liners. This rule requires a severe burnthrough test for ceiling and sidewall cargo liners in inaccessible cargo compartments. Cargo liners compliant with this test will prevent cargo/baggage fires from spreading outside the cargo compartment, maintaining flight control and protecting passengers and crewmembers.

Protective Breathing Equipment. This rule requires that transport airplanes must be equipped with protective breathing equipment to protect flight attendants from smoke while using fire extinguishers in fighting on-board fire.

Combi Cargo Compartment Fire Protection. Based in part on research and testing (Blake, 1996), this airworthiness directive requires certain design modifications and operational requirements to ensure an adequate level of fire safety in the cargo compartment of large "combi" aircraft (passenger and cargo compartments located on main deck).

In addition to the aforementioned implemented requirements, several other improved fire safety measures are under development or proposed. These include new fire protection requirements being developed for accessible cargo compartments in small airplanes because fire tests showed manual firefighting by flight attendants was ineffective and potentially dangerous. Finally, based on completed testing (Curran, 1993), FAA has proposed a new TSO for flight recorders which will include new fire test criteria aimed at assuring greater survivability in accidents accompanied by postcrash fire.

3. AGARD PROGRAM

The technical presentations planned for this AGARD Meeting on Aircraft Fire Safety are a good indication of research and testing activities since the last subject meeting in 1989. The meeting planners have organized the presentation into several sessions. The following is the keynote speakers synopsis of the subject matter that will be (hopefully) covered:

3.1 Aircraft Fire Safety - General Overview

This session has a number of papers on recent aircraft fire accident experience. Of interest is whether there is any discernible reduction in fire fatalities or improvement in fire survival that may be attributed to the fire safety design improvements described previously. Are there any trends with respect to the causes or contributing factors that point to needed

research? Have incidents occurred which may presage potential problem areas that need to be addressed?

3.2 Fires and Fire Handling

This session appears to deal with two subjects: application of computer modeling and airport firefighting. It is evident that computer models are now being employed in a number of applications. Of paramount concern to the end user (i.e., regulatory authority, aircraft manufacture/operator or airport operator) is the validity of the model. Also, what are the relative roles of full-scale tests and computer modeling predictions? With regard to airport firefighting, are there notable differences between civil and military airports? Important topics include the critical role of the firefighting commander in deploying available resources during fire extinguishment and rescue operations, and protection of personnel against residual fire dangers.

3.3. On-Board Fire Extinguishing Systems

Over the past 30 or more years, the primary fire extinguishing agents in civil and military aircraft have been Halon 1301 and Halon 1211. Selection of these "clean" gaseous agents was based on the following considerations: effectiveness over a wide range of operational conditions, low weight, low toxicity, compatibility with aircraft materials and virtually no cleanup required. Unfortunately, production of the marvelous halon fire extinguishants is now prohibited by international agreement because of their contribution to the depletion of the ozone layer. Replacement or alternative agents and systems are being tested and evaluated, but all have one or more deficiencies as compared to the halons, and many new agents have global warming effects or long atmospheric lifetimes that may be the focus of future restrictions. This session will cover the extensive research and testing activities driven by the ban on halon production, the dwindling supply of halon, and the lingering concern with a potential future-ban on halon usage (Federal Aviation Administrative, 1993).

3.4 Certification and Testing

Certification of aircraft fire safety design is primarily based on standardized fire test criteria. In aviation, fire test requirements cover a wide range of aircraft applications and fire threats, developed over a span of forty years. For example, the genesis of engine fire tests is in the 1950's while cabin material low heat release test criteria were developed in the late 1980's. This session will cover research activities to improve and better understand a number of aircraft fire test applications and to develop a test facility for burner can burnthrough, which is the most severe aircraft fire condition, basically a high temperature, supersonic jet.

3.5 Materials and Structure Design for Fire Safety

In terms of fire safety, the selection of aircraft materials and the structural design is based on two general considerations: (1) prevention of ignition or minimization of occupant exposure to fire hazards, and (2) protection of critical flight components so that the aircraft can be safely landed. This session will address a number of material and structural design considerations for aircraft fire safety, including basic research to develop ultra-fire resistant interior materials. Two papers will discuss the problem of fuselage penetration by a postcrash fuel fire, an important aspect of fire spread into the aircraft interior which is presently not explicitly addressed in fire safety design or test requirements.

3.6 Aeromedical Aspects Including Smoke Toxicity

Smoke and toxic products of combustion produced by an aircraft fire is a continuing subject area of research which is driven by a number of concerns, including the wide variety and large quantity of organic aircraft interior materials, confined passenger cabin environment, large number of occupants and possible long time of exposure to smoke and toxic gases. This session has a number of papers related to aircraft fire hazards, including the measurement of toxic gas levels, toxicity, burns and discriminating between fire and trauma fatalities. Of importance is the ultimate application of this type of research to the improvement of aircraft fire safety. For example, one paper will describe research into smoke control and ventilation during an in-flight fire. Although all organic materials produce toxic gases when subjected to fire or pyrolysis conditions, and inhalation of toxic gases is a major cause of aircraft fire fatalities, most fire researchers believe that selecting materials based on toxic gas or toxicity (animal) measurements during small-scale burn tests is not a valid approach for reducing enclosure fire hazards.

3.7 Passenger Protection and Behavior

Rapid passenger evacuation is the paramount consideration for passenger protection and survival during a postcrash fire. This session mainly deals with passenger evacuation research. Two papers describe computer modeling of the evacuation process. Of interest is whether model computations can supplement or replace the 90-second evacuation demonstration requirement, which is costly and injury prone. It would appear that this requirement, with its extensive data base from past demonstrations under well-defined conditions, provides the best basis for model development and validation. Two papers will describe evacuation research employing human subjects. Topics that will likely be covered include the critical role of flight attendants, effects of cabin configuration, passenger hesitancy in jumping onto a slide, etc. Also, experimental methods employed to induce human behavior believed to be an important factor in past accident evacuations, such as, passenger competition will be presented.

4. FUTURE RESEARCH CONSIDERATIONS

This AGARD meeting provides a good indication of the subject matter of aircraft fire safety research undertaken in recent years. Each of the research activities has its own merit. Nevertheless, as outlined below, there are a number of problem areas, highlighted by fire incidents, and fertile topics, that are also very worthwhile research activities.

4.1 In-flight Fires

The types of in-flight fire that can become a problem are those that originate in hidden or inaccessible areas. Hidden fires involve materials such as thermal acoustical insulation, wiring and cable, installed behind the cabin sidewall, above the ceiling and beneath the floor. Recent incidents and tests indicate that

the thermal acoustical insulation bagging material is a greater factor in flame spread than previously thought. Contamination is also a serious part of the problem. A number of hidden fires have occurred in-flight or on the ground which, in some cases, have gutted the aircraft. Investigation of these fires have revealed extensive contamination in hidden areas, for example, thick greasy dust on cable, stained insulation batt, grease, etc.

4.2 Electrical Wiring

Most aircraft in-flight fires are electrical in nature and are almost always controlled before having any effect on flight safety. At present, the only standard for aircraft wiring is a Bunsen burner flammability test. However, arc tracking failures have occurred in civilian and military aircraft. Also, electrical fires may cause high cockpit smoke levels, yet wiring selection in civil transports is not based on smoke emission. Finally, electrical faults from frayed wires have occurred in service because of failed or improper securing of wiring and cable. Therefore, more comprehensive test methods are required for electrical wiring as well as improved methods for securing and protecting cable and wiring.

4.3 Water Spray

FAA tests indicate that a cargo compartment water spray system may be an effective alternate to a Halon 1301 system (Marker, et al, 1996). Cargo water spray has several advantages although additional research is required to optimize the system. First, a water based system would not have the disadvantage associated with some chemical halon replacements; i.e., increased toxicity, potential global warming effects, and potential future environmental restrictions. Second, development of a cost effective cargo water spray system could make a similar passenger cabin system economically viable.

4.4 Fire Detection

Reliable and rapid detection of fire and smoke is critical to the effectiveness of intervention systems and procedures. It has been estimated that 90% of cargo compartment smoke detector activation's are false alarms. Also, although current regulations state that a cargo compartment fire detection system "must provide a visual indication to the flight crew within one minute after the start of a fire", there are currently no standardized test procedures to demonstrate compliance with this rule. Therefore, it is possible that the responsiveness to realistic fires varies for different approved smoke detection systems. Also, past FAA fire tests demonstrated that artificial smoke, used to certify photoelectric smoke detectors, indicated a more rapid response time than real smoke in detector systems employing vacuum sampling lines (Blake, 1985). Thus, a need exists for more reliable detection systems, including new designs employing non-traditional sensors, and standardized test procedures for the certification of aircraft detectors,.

4.5 Lavatory Fire Protection

Lavatories have been the source of several fatal in-flight fires (Varig, 1973; Air Canada, 1983), accounting for 146 fire fatalities. These accidents were the impetus for important improvements in lavatory fire protection, such as a cigarette smoking ban, fire hardening of trash receptacles, halon extinguishers ("potty bottles") and smoke detectors. Nevertheless, serious lavatory fires continue to occur. In 1993, an in-flight fire in the aft lavatory of a Dominicana 727 forced an emergency landing. All occupants escaped but the fire spread out of control and destroyed the aircraft. In 1995, an International Airlines DC-9 was gutted by fire while parked at a ramp in Barranquilla, Columbia. Investigators noted similarities between this unattended ramp fire and the Air Canada in-flight fire in 1983. The presence of potential ignition sources such as flushing motors, hot water heaters, lighting ballasts, and razor outlets, reported instances of improper passenger activity (detector tampering, smoking, etc.), and certain design features, such as high ventilation rates that may circumvent early fire detection, all point to the need for R&D to enhance fire protection design and crew firefighting procedures in aircraft lavatories.

4.6 Aerosol Cans

A relatively unrecognized potential fire safety hazard is the large number of aerosol cans carried in passenger luggage. Since 1979, aerosol cans have employed flammable hydrocarbon propellants including propane, butane and isobutane to replace the ozone depleting chlorofluorocarbons (CFC's). Conventional, three-piece aerosol cans burst and rocket when exposed to a fire. The remnants of discharged aerosol cans have been found in the contents of burned-out aircraft, although it has been difficult to establish what role the aerosol cans played in the fire. From full-scale fire tests, however, it is known that bursting aerosol cans release their hydrocarbon propellants, increasing the fire growth rate and, more importantly, may create rocketing projectiles that dislodge or penetrate cargo liners, violating design principles for cargo fire containment and allowing the fire to spread to other areas of the airplane (Blake, 1989). A safer aerosol can design has been developed, which withstands higher operating pressures and provides a mechanism for the controlled release of the can contents at elevated pressures (Daehn, 1994). Additional research is required to determine the benefit of improved aerosol cans during aircraft fires and to develop the design concept into a viable manufacturing process.

4.7 Oxygen Systems

Preventing fires caused by oxygen system malfunctions during servicing and maintenance will alone eliminate a significant number of hull losses. For example, inadvertent activation of an oxygen mask canister caused a fire that gutted a DC-10 in Chicago in 1986. Also, in Salt Lake City in 1989, replacement of an oxygen bottle during preboarding of a 727 caused an extremely intense fire that rapidly spread throughout the cabin. Fortunately, there were only a few occupants on board at the time and they were barely able to escape the fire that reached untenable conditions in an estimated 45 seconds. The potential large loss of life due to in-flight fire caused by oxygen system malfunction, similar to the above examples which occurred on the ground, or by a postcrash fire intensified by the release of oxygen is a great concern. Many of the 20 postcrash fire fatalities in the 737 accident at Los Angeles in 1991 may be attributed to the severed crew emergency oxygen system. FAA full-scale fire tests demonstrated a three minute loss of survival due to the release of oxygen into the postcrash fire (Marker and Downie, 1991). In the near term, methods of reducing the

quantity of oxygen accidentally released should be explored; i.e., flow restrictors, fuses or solid oxygen generators. The ultimate answer may be an oxygen generation system utilizing gas separation membrane technology, which would probably require a long term R&D program.

4.8 Hydraulic Systems

Aircraft hydraulic fluid has been the source of both in-flight and postcrash fires. In 1989 a 737 experienced a hydraulic fluid fire in the wheel well that resulted in an emergency landing and evacuation. Although there were no fatalities, the ingredients of a catastrophic accident were present; i.e., the fire caused loss of hydraulic pressure and breaking action, causing the airplane to overrun the end of the runway. FAA tests showed that hydraulic fluid spray contained in an enclosure such as a wheel well, may burn intensely if ignited (Blake, 1990). In 1980, a 747 experienced a crash fire following a hard landing caused by the sparking ignition of hydraulic fluid released by damaged struts. Fifteen people died from the postcrash fire in which there was no jet fuel spillage. There is sometimes a misconception that fire resistant aviation hydraulic fluid is noncombustable, but this is obviously not the case. Near term R&D is required to determine what improvements are feasible to prevent or minimize hydraulic fluid fires.

4.9 Future Aircraft

Fire Safety considerations in new aircraft designs, including the Very Large Commercial Transport (VLCT) and High Speed Civil Transport (HSCT), will be addressed in future R&D. The vulnerability of the upper deck in the VLCT and the impact on postcrash fire emergency evacuation and survivability is a major concern. Industry and government officials appear in agreement that carrying 800-1000 passengers, the VLCT must be designed to higher fire safety standards than contemporary airliners (Aviation Week and Space Technology, 1994). This attitude is not unprecedented. Tougher fire safety and emergency evacuation design criteria were imposed on the wide body jets when they were introduced into service in the early 1970's. With respect to the supersonic HSCT, the possibility of a composite fuselage skin raises a general question. Will the replacement of the non-combustible aluminum skin with an organic composite material impact HSCT postcrash fire survivability?

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Fire Safety and Fire Protection for Military Transport Aircraft as Addressed in a Recent NATO/AGARD Survivability Study

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1. Summary

This paper presents the major findings and conclusions related to fire safety and fire protection for military transport aircraft as determined by a recent NATO AGARD study. This study, entitled Enhancing the Survivability of Military Transport Aircraft (1), addressed all aspects of aircraft design for survivability including both susceptibility and vulnerability reduction techniques. However, in this paper we will focus only on those findings which relate to fire safety and protection.

The AGARD study looked at the survivability of military transport aircraft during humanitarian and peacekeeping operations, such as encountered in Panama, Somalia, and the former Yugoslavian states. Typically, transport aircraft are not designed to fly into hostile areas and thus have little protection against ground and air threats. However, with changing political policies and military doctrine, NATO countries have been increasing the utilization of military transports in these potentially hostile roles.

The AGARD study focused mainly on potential survivability enhancement retrofits for the current NATO tactical airlifters, the C-130, C-160, and G-222. However, survivability design features were also considered for potential new military transport aircraft such as the European Future Large Aircraft (FLA) and the conceptual United States (U.S.) Advanced Tactical Transport (ATT).

This study considered both aircraft susceptibility (inability to avoid being hit by a threat) as well as aircraft vulnerability (inability to avoid damage if hit). The main threats that were considered included; small arms (7.62 mm), high caliber projectiles (12.7 and 23 mm) and hand-held infrared missiles. Larger threats were also considered, but transport survivability against these were mainly dependent on avoidance and susceptibility reduction. Against the smaller threats, several vulnerability shortfalls in the area of fire protection were noted for the C-130, C-160, and G-222. The main shortfalls related to fire included; in-tank fire/explosion, void space fire/explosion, exterior fire, and hydraulic fluid fire. Engine fire was not considered a survivability problem since all aircraft in the study had adequate engine fire detection and suppression systems.

Many potential solutions were considered to reduce the risk of fire and explosion in order to enhance aircraft survivability. Both passive and active solutions were reviewed, including those used with other military aircraft, and the latest technology being used on the U.S. C-17 and V-22 transport aircraft. Solutions considered included; self-sealing fuel tanks and fuel lines, fuel tank ullage inerting, fuel tank foam (rigid open cell type), dry bay foam (closed cell type), and fire extinguishing systems.

The potential solutions were evaluated for ease of retrofit, applicability for new designs, operational restrictions, support requirements, weight, and cost. The major recommendations for retrofit on current aircraft included; fuel tank and dry bay foam, as well as fire extinguishing systems. The major recommendations for consideration in new designs included; fuel tank and fuel line designs to minimize vulnerable areas, self-sealing fuel tanks and fuel lines, fuel tank ullage inerting using onboard inert gas generation (OBIGGS), dry bay inerting, and fire extinguishing systems.

2. Background

In June 1994, the Advisory Group for Aerospace Research and Development (AGRAD) under the North Atlantic Treaty Organization (NATO), initiated a study on "Enhancing the Survivability of Military Transport Aircraft." This study, conducted by Aerospace Applications Study Group 41, had the goal of identifying measures to enhance the survivability of unescorted military transport aircraft while operating on humanitarian or peacekeeping type missions. These types of missions could be subjected to a wide range of threat environments, such as those encountered during past operations in Panama, Somalia and the former Yugoslavian states.

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

The AGARD study team consisted of over 30 experts, representing eight nations and various technical backgrounds including; aircraft design engineers, subsystem engineers, avionics engineers, operational research analysts, and aircraft operators. This team brought together a diversified level of expertise to address the survivability of military transports in the humanitarian and peacekeeping roles.

In the past, the design of military aircraft gave little, if any, consideration to fire protection from damage caused by external threats. The earliest known considerations were applied to U.S. Air Force aircraft such as the OV-10 (1964), F-15 (1969), and A-10 (1973) (2). However, for transport type aircraft there was no initial design consideration for survivability until the 1980's with the McDonnell Douglas C-17 and Bell/Boeing V-22. (Although there have been several retrofit applications on transports since the Vietnam-era.) It was not expected that transports would be exposed to hostile threats due to their operations mainly in the background of a battlefield. However, in today's scenarios, transports are expected to operate in hostile environments to implement direct delivery to combat forces. In addition, new scenarios are emerging in the areas of humanitarian aid and peacekeeping which are exposing transports to an increasing number of hostile threats. For example, the United Nations supported only two peacekeeping missions in 1950, but a record 18 in 1993.

The AGARD study group was tasked to assess the risks associated with military transport operations in both humanitarian and peacekeeping missions, as well as to identify measures to counter or reduce these risks. Mitigation techniques could include;
1) operational procedures,
2) active and/or passive countermeasures, and
3) physical protection and/or shielding of the aircraft.

This paper will focus on the physical protection side of this survivability study. It is realized that transport aircraft contain many critical systems that need to be protected from external threats including; flight controls, electrical, hydraulic, environmental, propulsion and fuel systems, as well as the flight crew. Based on years of research in these areas, many protection techniques have been explored and in many cases implemented for the critical systems on newer military transport aircraft. One of the most critical and probably most vulnerable system, the fuel system, continues to be the focus of extensive research, as designers attempt to find improved protection techniques. Improvements are basically focused in the areas of lower weight and cost, as well as better reliability and maintainability.

This paper will focus on vulnerability and protection techniques for the fuel systems. The protection of these systems in military transports has been the subject of study for nearly 30 years, since C-130's were pressed into high threat operations in Vietnam and retrofit solutions were required. This study did not attempt to perform specific research on fuel system protection, but instead reviewed and evaluated several state-of-the-art protection techniques which were employed or considered for various transport aircraft.

3. Aircraft

The AGARD study focused on the current military tactical transport aircraft employed by NATO countries. This included the Lockheed Martin C-130, the VFW/MBB/Aerospatiale C-160, and the Alenia G-222 (Figure 1). In addition, design recommendations were considered for potential new military transport aircraft such as the European Future Large Aircraft (FLA) and the conceptual U.S. Advanced Tactical Transport (ATT).

Currently there are approximately 125 C-130's in operation with Belgium, France, Greece, Italy, Spain, Turkey, and the United Kingdom. In addition, about 610 are in operation in the United States. The second aircraft under consideration, the C-160, is in operation in France, Germany, Turkey, and South Africa, with a total of 220 aircraft. The G-222 is in operation with 12 countries with 108 aircraft in service. Typical missions for all of these aircraft include humanitarian and peacekeeping support roles.

4. Threat Systems

The AGARD study considered three threat levels which represented three levels of weapon sophistication. It is realized that in the real world there may not be such a clear division of threats, but these levels allowed an organized framework for review and analysis of multiple threats.

Threat level 1 was assumed to consist of small arms, optical anti-aircraft artillery (AAA), and early generation shoulder-launched surface-to-air missiles (SAMs), such as the SA-7 and basic Stinger. It was assumed that there was no integration of distributed air defense systems. This threat level could be representative of that which would be encountered during humanitarian missions. In addition, these threats could also potentially be encountered in any location, at any time, including during peacetime operations when a transport could be subjected to terrorist actions.

Threat level 2 included radar directed AAA, early radar-guided SAMs, and third generation infrared SAMs, as well as the systems present in threat level 1. This threat level assumed a moderate level of air defense integration. This threat level is more likely to be encountered during peacekeeping type missions flown in areas of conflict involving small and/or medium sized political powers.

Threat level 3 comprises advanced radar- and IR-guided SAMs, plus directed energy systems, as well as the systems present in threat level 2. At this level, a well integrated air

defense system is assumed. Threat level 3 is only expected to be encountered in areas of high density conflict between major world powers. Due to this extreme environment, military transport aircraft would not operate unless escorted by multiple support aircraft. This threat level is not expected in humanitarian or peacekeeping missions, and thus was not analyzed in much depth during this study.

5. Military Transport Aircraft Vulnerability

Aircraft vulnerability is a measure of an aircraft's inability to withstand the damage effects of a threat encounter. In general, aircraft vulnerability can usually be reduced by increasing the redundancy, separation, and/or damage tolerance of critical systems and components.

An aircraft can be divided into subsystems, each of which performs an essential aircraft function. A threat encounter can cause damage that degrades the capability of the aircraft by degrading the operation of one or more of the aircraft subsystems. The critical aircraft subsystems of the C-130, C-160, and G-222 include; flight controls, hydraulics, propulsion, fuel, electrical power, and structure, as well as the flight crew. Severe damage to any one of these subsystems can lead to the loss of the aircraft. The focus of this paper is on fire safety and protection and in this respect concentrates on fuel system vulnerability and protection techniques. It is recognized that fires can occur in other areas such as the hydraulic system and/or cargo bay, but these are considered lower risk areas. Details on other systems can be found in the full AGARD study (1).

6. Aircraft Fuel System Vulnerability

An aircraft fuel system includes those components and equipment which are used to store, distribute, and deliver fuel to the aircraft engines. In a military transport aircraft, these components will typically consist of; fuel tanks (internal and/or external), fuel lines, pumps, valves, and monitoring systems. Due to their large inherent size and flammable fluid, fuel systems are usually the largest contributor to the aircraft's vulnerable area. However, with proper attention to fuel system protection, a large amount of aircraft vulnerability reduction can be achieved.

6.1 Current Aircraft Fuel Systems

The following paragraphs provide basic descriptions of the fuel systems and fuel tank layouts of the three aircraft under study in this paper.

The C-130 Fuel System.

The C-130 fuel system is a modified manifold-flow type, incorporating a fuel crossfeed system, a single point refueling and defueling system, a fuel dump system and, on some versions, an inflight refueling system. The system provides the fuel for the four engines and the gas turbine compressor. System design is adaptable to a number of flow arrangements. Each engine may be supplied with fuel either directly from its main fuel tank, or through the crossfeed manifold system from any other tank.

Six fuel tanks are located within the wing. Four of the six tanks are an integral design. These are located in the outboard portion of the wingbox, two each in the left and right wings. Left and right auxiliary fuel tanks, comprised of three bladder-type cells interconnected to form a single assembly, are located within the center wing section. Each tank has an ac-powered boost pump to generate fuel flow. On some C-130's, two additional external tanks can be mounted under the wings on pylons between the inboard and outboard engines. These tanks are constructed of metal and are partially compartmentalized (to aid in center-of-gravity control). Each tank contains two boost pumps to maintain adequate fuel flow.

All of the fuel tanks are vented to the atmosphere to equalize pressure at all times. A fuel dump system is provided to enable all but about 15% of the fuel to be dumped overboard.

The C-160 Fuel System

In the C-160, each side of the fuel system is designed to supply either one or both engines and the auxiliary power unit (APU). Fuel storage is provided by two integral tanks in the outer wing box of each wing. The two tanks are separated by a sealed rib while intermediate ribs are provided to prevent fuel surge effects. The tanks have no self-sealing capability. During normal operation the tanks in the left wing supply fuel to the left engine and those in the right wing provide fuel to the right engine. If required, however, the left tank can also supply fuel to the right engine and vice versa. Each engine system is supplied by four submerged electric fuel pumps, one at the front and the other at the rear of each integral tank. The APU is supplied by the crossfeed manifold system. The tanks can be refueled by single point refueling or by gravity. First generation C-160's have no fuel dump capability.

The fuel system design for second generation French C-160's (from 1980) is slightly different. These models have two additional integral tanks in the center wing section, and a fuel dump system. The pumping group in the dry bay of the center wing section consists of four pumps and allows in-flight refueling, fuel transfer from the center tanks to the integral wing tanks, and fuel dump. Some second generation C-160's are equipped for inflight refueling using the probe and drogue system.

The G-222 Fuel System

In the G-222, the fuel is supplied to the engines and APU from four integral wing tanks; two main tanks and two auxiliary tanks. One main tank is located in each wingbox,

outboard of the engine nacelles. The two auxiliary tanks are located inside the wingbox in the center span section. The tanks located in the left wing provide fuel for the left engine as well as the APU. The tanks in the right wing provide fuel to the right engine only. Each of the four tanks is equipped with two submerged electric boost pumps to feed the engines. An additional pump is located inside the main left tank to feed the APU. A cross feed system is available to allow each tank to feed each engine. The tanks can be refueled either by gravity (four fill ports on top of wings) or by a single point system in the wheel well. A system of electrical valves allows in-flight fuel dump from each tank. The tanks are integral with the wing structure and the internal surfaces are protected with a anti-corrosion treatment and sealant.

6.2 Fuel System Vulnerability Versus Current Threats

Past combat experience has shown that the fuel tanks are the largest single contributor to transport aircraft vulnerability. This is mainly due to their large presented area, which increases the probability of a hit, and the flammability of the fluid. Fuel tanks are typically vulnerable to being hit by small arms and AAA projectiles (both high-explosive (HE) and armor-piercing (AP)) and by fragments from exploding missile warheads.

There are essentially three failure modes for a damaged fuel system;
- fuel supply depletion or starvation,
- fire and explosion, and/or
- hydrodynamic ram.

Fuel supply depletion or starvation may occur when a threat penetrator or fragment damages a critical fuel system component that results in a fuel leak or blocks the transfer of fuel to the engine. Fuel system components which are critical include the tanks, fuel lines, valves, and pumps. All of the study aircraft have multiple pumps and tanks which provide sufficient levels of separation and redundancy to preclude fuel depletion or starvation. Thus, the study aircraft are considered to have inherent protection against this failure mode.

The second damage mode, fire and explosion, is the main focus of this paper. This damage mode can occur mainly in two places;
- within a tank in the air spaces above the fuel (ullage), and
- outside of the tank, in the dry bays which surround the tank walls.

The study aircraft contain both integral tanks and bladder-type fuel cells. An integral tank is formed directly by the wing structure which makes up the tank walls, whereas a bladder tank is a self contained vessel placed within the wing box. Figure 2 shows these two representative fuel tank arrangements and illustrates potential vulnerable areas in the ullage and dry bays.

The ullage inside the fuel tank can contain a highly explosive atmosphere when the appropriate fuel-air mixture is present. Initiation of an explosion is primarily caused by an ignition source such as the incendiary particles released by a projectile, or a vaporific flash (the spark caused during the penetration of a projectile or fragment). A fire in an adjacent dry bay can occur when a ballistic penetrator creates a hole in the wetted region of the fuel tank wall, thus creating a fuel leak into the dry bay. In addition to incendiary and vaporific flash, fire ignition in a dry bay can also be caused by hot equipment or a ruptured bleed-air line.

Ullage and dry bay spaces are very vulnerable to fire and explosion. Due to their relatively large presented areas, they are a large contributor to the aircraft's total vulnerable area. Of the three study aircraft, only the C-130 has a ullage explosion suppression system (see discussion in Section 7.1). None of the aircraft have any dry bay fire suppression capabilities.

The final fuel system damage mode, hydrodynamic ram, is produced when a projectile penetrates a fuel tank wall and enters an area of an enclosed fuel volume. As the projectile traverses the fluid, pressure pulses and waves are generated by various fluid dynamic effects. The end result can vary from minor leaks to complete fuel tank rupture. The details of this failure mode and potential protection techniques are beyond the scope of this paper. However, it is mentioned here as it could lead to a source for a fuel fire.

7. Fire/Explosion Protection in the Fuel System

Most current military transport aircraft lack any substantial protection against fuel system related fire and explosion (i.e., ullage explosion, dry bay fire, and engine fire). The C-130, C-160 and G-222 were all originally designed without requirements for fuel system vulnerability reduction. Once an aircraft design is "frozen" it becomes very difficult and costly to retrofit fuel system protection features. However, there are several options that may be considered, each with various levels of effectiveness and weight/cost penalties. Past methods have included; reticulated foams, liquid nitrogen inerting, Halon inerting, and onboard inert gas generating systems. Figure 3 provides a list of the most common fuel tank protection techniques in which the U.S. and other NATO Air Forces have extensive experience.

Vulnerability reduction modifications will often result in fuel volume loss and/or a gain in aircraft empty weight. This results in reduced payloads and/or reduced range. However, for aircraft that will be subjected to threat encounters, fuel system modifications should definitely be considered due to the large vulnerable area of fuel systems.

Fires and explosions can occur in the engine compartment, fuel tank ullage, and void spaces around the tanks. Fire

prevention/suppression in the engine compartment typically consists of a warning system and extinguishing agent, along with structural fire walls to prevent migration. Fire prevention/ suppression in the fuel tank ullage and void spaces is a more challenging task due to the larger areas involved. Typical methods include the application of foams and fillers, or fuel vapor inerting and/or purging.

The following sections describe some of the methods and techniques which could be used to protect the fuel system in military transport aircraft from fire and explosion. The full AGARD study reviewed many other candidate methods, but this paper will focus on those techniques submitted as recommendations. First, methods are described for potential retrofit in the current fleet. Then a potential solution is described for consideration in future military transports.

7.1. Prevention/Suppression of Fires and Explosions in Current Military Transports

Fire Warning and Suppression

Fire warning and extinguishing systems are commonly installed in aircraft engine compartments and commercial aircraft cargo holds. They consist of temperature sensors to warn of an overheat condition and an extinguishing agent, such as Halon, to blanket the fire. These systems are considered "active" systems and typically are used only after a fire has started. In addition to engine compartments and cargo holds, this method is also found on some military aircraft for fuel tanks and dry bays. The basic principle of fire detection followed by extinguisher dispersal is the same. The differences appear in reaction times, dispersal patterns, and dispersal rates.

Fuel Tank Ullage Protection

For current military transports, a cost-effective method to prevent/suppress fires in the ullage and void spaces is to employ rigid or flexible, light-weight, polyurethane foam. The foam functions as a mechanism which absorbs and transfers heat away from an ignition source, reduces combustion overpressure, and breaks up compression waves that precede the flame front in an explosion. Additionally, foam has a high surface to volume ratio that enables the strands to collect a fine film of fuel, thus promoting an enriched vaporous mixture in the unfilled portions of the tank. The flexible foams have been available in five types as summarized in Table 1.

The principal drawbacks of using foam include weight and range penalties. The weight penalty will depend on the volume of tank which is occupied by foam. The entire tank does not need to be filled, but only that volume which will provide a sufficient reduction in ullage overpressures following ignition of the flammable vapor. Typical past applications have required ullage fills of less than 50%.

Once an engineering analysis determines the volume of foam required (i.e. 30% to 100% of ullage), then the weight required for application to the C-130, C-160, or G-222 can be calculated using the foam densities in Table 1.

An example of a foam retrofit application can be seen in the C-130. The USAF has been using a reticulated polyurethane foam to successfully suppress explosion and fire in the C-130 since the late 1960's. Initially, the foam was the polyester Orange Type I with a nominal 10 pores per inch and density of 1.8 pounds per cubic foot. However, it was found that this material was susceptible to hydrolytic degradation which shortened its service life. This is where high temperature and humidity cause the foam to deteriorate and create debris in the fuel system. Better materials with improved hydrolytic stability and lower weight were developed using a "hybrid" polyether material. This new foam is manufactured in the blue colors and is currently in use in the USAF C-130's.

The C-130H aircraft has four integral wing tanks, two auxiliary fuel tanks, and two external pylon tanks, with a total fuel capacity of 9,800 gallons. As a retrofit, foam was installed in all of the tanks. The size of the access openings into the tanks determined the size of the foam pieces that could be installed. The total volume of foam installed in the C-130H was 1,148 cubic feet which added a weight of 1,543 pounds. With the foam installed, the usable fuel lost amounted to a total of 432 gallons; 216 gallons due to volume displacement and 216 gallons that cling to the foam.

For protection in the void spaces surrounding the fuel tanks, both rigid (closed-cell, nonporous), and flexible foams can be utilized. In this application, the dry bays around the tanks can be filled with molded blocks or spray-on foams. This will help to prevent formation of an explosive environment caused by an accumulation of flammable vapors due to a fuel system leak or rupture. Typical weights for the rigid foam range from 1.5 to 2.5 pounds per cubic foot. To be of greatest effectiveness, the dry bays should be completely filled with the foam. The drawback of this type of application is that there is typically a negative impact on maintainability. If foam covers a component, the foam must be removed to allow inspection and/or repair.

In addition to foam, other materials, such as lightweight fibrous fillers, and expanded aluminum meshes, have been utilized in fuel tank ullages and void spaces. They function much like foam in that they interrupt the combustion process and suppress the combustion overpressure.

7.2. Prevention and Suppression of Fires and Explosions for Future Military Transports

When designing a new transport aircraft, fuel system protection can be incorporated from the start to minimize the risks of fuel system fire and/or explosion. Basic design

philosophies, such as those documented in references 3 and 4, have been incorporated into fighter/attack type aircraft and should also be considered for military transports. Due to their relative large size, transport aircraft are more readily adaptable for system redundancy and separation. The major design philosophies that should be considered for transports include;

- Fuel system redundancy - dual tanks and dual feeds to engines. This alone does not protect an aircraft from fire or explosion, but provides a level of safety if one of the tanks is damaged by fire/explosion.
- Fuel system separation - provide the greatest distance possible between the redundant components of the fuel system. This will minimize the possibility of a single threat impact causing damage to the redundant fuel system components. Separation also minimizes the possibility of a fire and/or explosion in one system from spreading or effecting the other system.
- Ignition source isolation - fuel system components (tanks, pumps, valves, lines, etc.) must be isolated from potential ignition sources through the use of separation, firewalls or other protective blankets and/or covers.
- Control leakage path - fuel system design should take into account potential leakage paths. The design should incorporate channels/drains that would direct any fuel leaks away from potential ignition sources.
- Masking/shielding of critical fuel system components - aircraft design should take into account the fuel tank and fuel component locations with respect to other aircraft structure and systems. To the extent possible, fuel system components should be masked and shielded from potential threat directions, by placing tanks behind structure and other less critical systems. Specific shielding can also be provided in the form of "armor" type material.
- Fuel tank shape - the fuel tank shape should be optimized to minimize the presented area in the direction of the threat.
- Passive and active protection systems - specific fuel system protection techniques should also be considered. This could include passive systems such as self-sealing tanks or polyurethane foams. In addition active systems such as fire detectors, suppressers, and extinguishers are also available.

The most common passive systems, such as foams and fillers (discussed in Section 7.1), will interrupt the combustion process before it becomes explosive. However, methods of inerting the ullage fuel/vapor mixture will prevent combustion from occurring in the first place. This is accomplished by reducing the oxygen concentration of the ullage fuel/vapor mixture to a level too low to support combustion. Common methods of fuel tank inerting use nitrogen, carbon dioxide, or Halon to replace the oxygen that resides dissolved in the fuel as well as that found in the open spaces of the fuel tank and vent system.

Fuel Tank Inerting

Fuel tank inerting methods have been in use for some time on aircraft such as the A-6, F-16, and C-5. Even the SR-71 uses inerting, not for threat protection but for protection from possible spontaneous ignition from the high structural temperatures encountered at supersonic cruise speeds (5). Many different methods and many different agents have been explored, tested, and utilized to accomplish fuel system inerting. Methods include dilution, scrubbing, and purging, and agents have included nitrogen, carbon dioxide, and Halon. Nitrogen inerting has proven popular due to ease of generation and handling and due to logistics problems encountered with many of the other agents. Nitrogen can be supplied in three ways; bottled cryogenic liquid, bottled high-pressure gas, and onboard generation.

The dilution method of inerting would involve feeding an inerting agent such as nitrogen into the top of a fuel tank to fill the void as the fuel level goes down. This is accomplished in closed-vent systems. The purge method would involve pumping nitrogen into the void area to sweep the fuel/vapor mixture out through an open vent system. The scrubbing method involves bubbling nitrogen up from the bottom of the tank in order to collect dissolved oxygen and carry it to the upper void area. This mixture is then purged.

The selection of an inerting method and inerting agent is best accomplished during the preliminary design phase of an aircraft in order to ensure a cost effective approach. For example, in the case of the U.S. Air Force McDonnell Douglas C-17, extensive analysis and testing was accomplished to ensure the optimum use of vulnerability reduction features for the fuel system.

The fuel system protection techniques identified for the C-17 form a basis for design considerations for future military transports. For example, the fuel system contains redundancy and separation through four independent fuel tanks along with an internal crossfeed system. Fuel tank inerting is accomplished via an onboard inert gas generating system (OBIGGS) (6). This system generates nitrogen-enriched air, which is used to inert the fuel vapors in the fuel tank ullage area. Vapors are kept below an oxygen level of 9% which is the ignition threshold. This nitrogen inerting system greatly reduces fuel tank vulnerability to small arms fire and fragment penetrations which could cause fuel vapor ignition and explosion.

The AGARD study evaluated several other alternatives to accomplish fuel tank ullage inerting. One of the methods considered was that which is used on the C-5 military transport. Here fuel tank inerting is accomplished through the use of liquid nitrogen (LN2). Before departure, the LN2 is uploaded and stored in cryogenic bottles. When needed, the LN2 is vaporized using a heat exchanger and delivered to the fuel tanks to maintain an inert ullage atmosphere (9% oxygen maximum). The advantage of the

LN2 system is that it allows very low oxygen concentrations in the ullage and contains a minimum of moving parts. However, due to container and weight limitations, only a limited supply of LN2 can be carried on the aircraft. After it is used the aircraft needs to replenish at a logistics base. Also, additional safety procedures are needed due to the handling of cryogenic material.

Halon, commonly used as an extinguishing agent, can also be used as an inerting device for fuel tank ullages and dry bays (as in the A-6 and F-16). In these cases, Halon will be dispensed into these spaces prior to the aircraft entering a high threat area. For future applications, a substitute extinguishing agent will be required as Halon is being banned worldwide due to environmental issues.

After evaluating foam alternatives, inert gas, and other options, it was determined that the most cost effective method, for a new aircraft design, would be fuel inerting through the use of nitrogen enriched air (NEA) supplied by an OBIGGS system. As previously mentioned, this approach is in use on current production aircraft such as the USAF C-17 and V-22 and has been sufficiently tested to be considered a low risk for applicability to future military transports.

On-board Inert Gas Generation System (OBIGGS)

Nitrogen gas has been found to be an effective fire/explosion inhibitor and is very well suited for application in aircraft fuel tank systems (4, 5, 7). However, the amount of nitrogen needed to provide protection for an entire mission can incur a large weight penalty on the aircraft if it must be carried from take-off to landing. A solution to this problem is the On-Board Inert Gas Generator System (OBIGGS).

The OBIGGS approach using nitrogen was deemed the best solution for future military transports due to relative low weight, no direct displacement of fuel, ease of maintenance, and effective inerting qualities compared to other alternatives. Although it has a higher initial cost than some other solutions, it appears to have the lowest life-cycle costs.

Two basic types of OBIGGS systems have been developed, "continuous flow" and "stored gas" systems.

In the continuous flow system, inert gas is generated and fed into fuel tanks on a continuous basis. The rate of generation must keep up with the maximum demand rate which will be dictated by the maximum fuel burn or descent rate. This system is best suited for aircraft with relatively low fuel burn/descent rates, such as the U.S. AH-64 Apache, for which it is in service. This system has the advantage of low weight and fewer mechanical parts compared to the stored gas system.

In the stored gas system, inert gas is generated in the same manner, but is then compressed and placed in high pressure storage tanks. Gas from the storage tanks feed the fuel tanks during descent and to makeup for fuel-burn. Stored gas is better suited to keep up with rapid descents. Another advantage of stored gas is it can be used during a "ground sit" to maintain fuel tank inerting even with no power on the aircraft. The disadvantage of stored gas is the requirement for a compressor and storage tank system, which adds weight and cost. However, it is still the best solution for large aircraft with rapid descents rates. This system is in use on the C-17 and provides fuel inerting during tactical descents of over 10,000 feet per minute and also during "ground sits" of up to 48 hours.

Figure 4 provides a general schematic of a stored gas OBIGGS system. The process begins with high pressure engine bleed air ducted into an air separation module (ASM). The ASM is the key component of the OBIGGS as it provides the mechanism to separate the oxygen from the air supply, resulting in air with a higher percentage of nitrogen, commonly referred to as nitrogen enriched air (NEA). The NEA then passes to the OBIGGS compressor unit where it is pressurized to 3,000 psi. It is then ducted to the storage cylinders, while the waste product is usually vented out of the aircraft. The storage cylinders then feed the fuel tanks to continuously purge the fuel/air vapor in order to maintain an inert ullage environment.

There are two techniques that are used in air separation modules to produce NEA; the molecular sieve or the permeable membrane approach. The molecular sieve technique generates the inert gas by means of a pressure swing absorption system that uses a zeolite molecular sieve material through which the supply air passes to produce NEA. The permeable membrane technique utilizes hollow methylpentane fibers, arranged in a cylindrical bundle around a hollow mandrel. As intake air flows through the mandrel, oxygen preferentially permeates through the fibers, thus generating an inert gas which passes through and is collected at the end of the bundle.

An example of the molecular sieve method can be seen on the C-17 (6). Two interconnected, but independent systems are used to provide redundancy. One ASM provides for each half system, and each module has three zeolite beds that extract oxygen from pressurized air. As each bed becomes saturated, it is vented overboard and excess oxygen and moisture are released. The resulting NEA is ducted to the compressor. This system can supply 50 pounds (22.7 kg) of NEA per minute per wing as required to maintain inerting during steep descents.

8. Recommendations and Conclusions

This study reviewed many options available for fuel tank protection against fire and explosion. This included both traditional and state-of-the-art methods that have been in use in fighters and transports. In the full AGARD study, the potential solutions were evaluated for ease of retrofit, applicability for new designs, operational restrictions, support requirements, and weight and cost.

For the current military transports (C-130, C-160, and G-222), the main recommendation was to consider retrofitting a limited number of aircraft with flexible fuel tank foam and rigid dry bay foam. This should be accomplished only for the few (10-20) aircraft which would be expected to support missions in hostile areas. For longer term solutions, or for a fleet wide retrofit, it is recommended that an OBIGGS inerting system be considered, due to the high weight of the foam approach. The following table shows a summary of the weight and cost trade-off for these options.

Current Aircraft (C-130, C-160, G-222)

Estimates for C-160	Weight	Cost ($US)
Foam	2200 lbs.	10K
OBIGGS - Continuous flow	600 lbs.	100K
OBIGGS - Stored gas	600 lbs.	300K

The main recommendations for consideration in new designs included; fuel tank and fuel line designs to minimize vulnerable areas, self-sealing fuel tanks and fuel lines, fuel tank ullage inerting using onboard inert gas generation (OBIGGS), dry bay inerting, and fire extinguishing systems. The following table summarizes the weight and cost of using an OBIGGS system on an FLA aircraft.

Future Aircraft (FLA, ATT)

Estimates for FLA	Weight	Cost ($US)
OBIGGS - Continuous flow	1000 lbs.	170K

It is noted that theses estimates were based on a continuous flow system which does not have the weight and cost of compressors and storage bottles as used in a stored gas system. However, added weight would come from the requirement for a larger ASM which is needed to keep up with the NEA demand.

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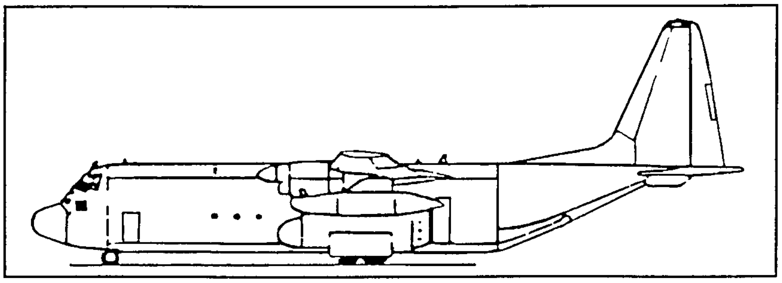
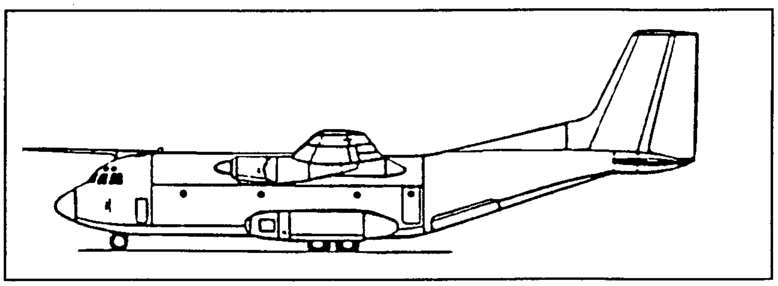
Lockheed Martin C-130



VFW/MBB/Aerospatiale C-160



Alenia G-222

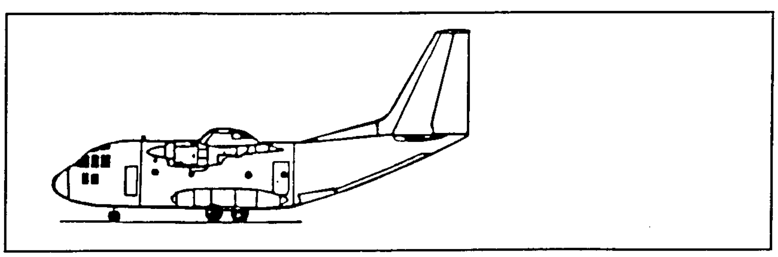
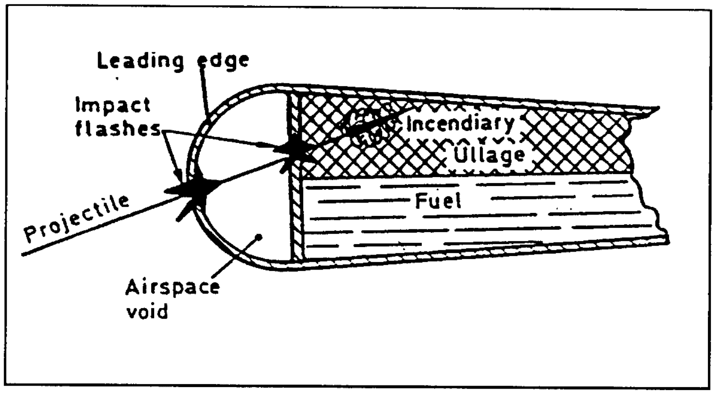
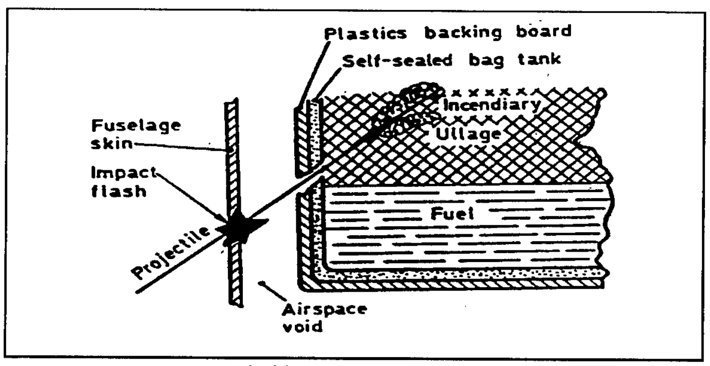


Figure 1. Current NATO Tactical Transports.



Integral Wing Tank



Bladder-Type Fuel Tank

Figure 2. Representative Fuel Tank Arrangements - Fire and Explosion Vulnerability.

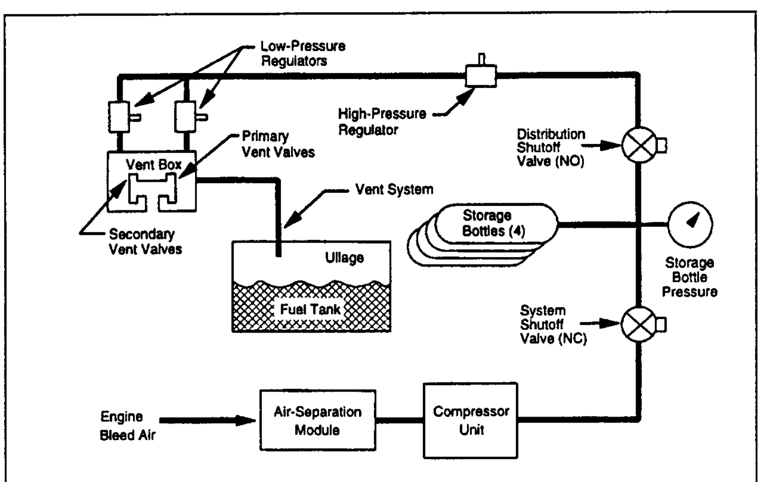
Passive Techniques

Flexible, polyurethane foam
Rigid, closed-cell foam
Void fillers (fibrous and aluminum foil)
Powder packs
Antimisting fuel
Void venting
Inerting - Halon
Inerting - Nitrogen (liquid, gas, onboard generation)

Active Techniques

Ignition source detection and combustion suppression
Hydraulic pressure detection and combustion suppression
Fire detection and fire extinguishing

Figure 3. Representative Fuel Tank Protection Techniques.



OBIGGS Operation

Figure 4. General Arrangement of an OBIGGS System.

Table 1. Flexible Foams for Fuel Tanks.

Foam Type	Name	Material	Density (lb/ft3)	Pores/inch
I	Orange	Polyester	1.8	10
II	Yellow	Polyester	1.3	15
III	Red	Polyester	1.3	25
IV	Dark-Blue	Polyether	1.3	15
V	Light-Blue	Polyether	1.3	25

A Review of Fire Related Accidents, 1985 - 1995

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1. ABSTRACT

In the 1975 and 1989 AGARD Symposia statistics were presented concerning the survival aspects of transport aircraft accidents. Although much relevant data was still missing it was concluded that not much had changed in the intervening years. Following the Manchester B737 fire accident in 1985 many important recommendations were made and much research has been completed. The current study reviews relevant accidents 'post-Manchester' and tries to assess to what extent the changes that have been made have improved our chances of escaping safely from an aircraft that is on fire or has been damaged sufficiently for fuel to have been spilt.

As far as possible criteria identical to those used previously will be employed in order to make the comparisons valid, however it must be appreciated that international aviation is changing and any effects of these changes that can be quantified will also be discussed..

2. INTRODUCTION

It is not unusual for the Abstract of a paper to be written well before the paper itself and for intervening events to require some alteration to the route originally anticipated. The above Abstract, written in June 1994 for the following paper, written two years later is no exception thus, before discussing post-Manchester accidents, a variety of points of a more general nature will be made.

Previous papers (references 1 and 2) have suggested that in order to proceed along the route towards ever safer air transport we need to consider not only single significant accidents but also more general trends and pointers as may be gleaned from a study of accident statistics. The implication was that such consideration would lead to sensible and effective action. But has it? - that is the important question and if not, as will emerge, how should we organise matters in the future to ensure the progress that the ever increasing numbers of flights per year makes essential?

In an ideal world the investigation and reporting of incidents would prevent accidents but human nature being flawed, particularly when affected by financial and legal pressures, we are still some way short of this ideal. What may happen after an accident is that the investigator discovers that there has been at least one previous similar accident and any number of related incidents. The former had been treated as a 'one off' and the incidents as being of no real significance since they had not led to an accident!

Reference 3 pointed out that, to paraphrase the immortal Lady Bracknell in Oscar Wilde's 'The Importance of Being Earnest', it may be said that *'to lose one aircraft may be regarded as a misfortune, to lose two looks like carelessness'.* Thus the dedicated and, it is sometimes said, idealistic work of the accident investigators may be dismissed since a single accident, being merely a misfortune, does not seem to merit any extensive and perhaps expensive action. Now of course if we have a second, something must be done immediately!

Once upon a time this approach paid valuable dividends; no country, airline or manufacturer had to wait very long for a second or even a third accident so, whether due to carelessness or something else, the cause was not only found but acknowledged and action taken. As a result the accident rate fell and fell. That is history, or is it? Henry Ford, who got quite a few things right, told us that *'history is bunk'.* If this means that we still fail to learn from or at least fail to act upon the lessons from the past, then many would agree.

How often has it been said that we must learn from the mistakes of others because we won't live long enough to make them all for ourselves? How often has this been misinterpreted as meaning we could live a full three score years and ten and not make them all when what is meant is that the first or, if we are lucky, the second or third mistake could take us to a very early grave?

How many conferences, like this one, related to safety or accident investigation have started with a paper on accident statistics? How many of us have actually left with both a knowledge of what should be done and a will to do it? What is there in human nature that makes us so resistant to making changes? Why do we expend so much effort on finding reasons for not making a change? Why do we stick so rigidly to the first reason we think of?

It is suggested that there is neither a simple nor a single answer to most of these questions though one which has often been given over the last few years may be relevant. The increasingly litigious nature of the aftermath of an accident, in which lawyers claim that making a change is an admission that matters were not right before and is therefore an admission of liability, does not encourage change. This should of course be balanced by the fear of being caught out by a further accident before a change has been made when circumstances clearly, at least to the lawyer with 20/20 hindsight, show an early change to be necessary. The fact that preference seems to be given to the status quo may possibly be explained by the belief that the further accident will not occur, at least not until long enough afterwards for the earlier circumstances to have been forgotten or for the personnel to have changed. Nevertheless, in some cases, there are of course perfectly genuine reasons for **not** making a change, the facts have to be weighed up very carefully.

3. LEARNING LESSONS FROM PAST ACCIDENTS

An example from a different type of accident illustrates the apparent reluctance by airworthiness authorities and manufacturers to make changes. In October 1971 a Vickers Vanguard crashed in Belgium, killing all 63 on board, due to a failure of the rear pressure bulkhead allowing cabin air into the tail cone and hence into the horizontal stabiliser. The

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

stabiliser could not withstand the pressure, 'blew up' and detached (reference 4). This accident has been amongst those presented at Cranfield (reference 5) each year, from 1978 onwards, to airworthiness and design engineers from Europe and beyond, as an example of how the catastrophic secondary consequences of a serious but non-catastrophic primary failure could be overlooked or ignored by design and certification teams alike. The August 1985 accident to a B747 in Japan, for very similar reasons and with the loss of 520 of the 524 on board, therefore came as a very nasty shock and a reminder that discussing an accident, without checking that proper action **has** been taken, does not prevent the next. This point was made in subsequent lecture notes. What was even more alarming was that even then no action was taken and it appears to have been only after a similar but fortuitously non-fatal accident to a Tristar over Manchester in December 1990 that regulations were eventually amended.

This is where it has been suggested that accident statistics can help. Is an accident a one-off or is it one with many similarities to previous accidents? The inference is obvious and has been spelled out many times before (references 1 and 2) nevertheless a question remains as to whose job it is to point out the similarities.

In the UK the Air Accidents Investigation Branch (AAIB) of the Department of Transport investigates accidents and is meticulous in determining the facts, analysing them, drawing conclusions and making recommendations. The Civil Aviation Authority (CAA) then considers the recommendations, decides whether or not to act on them and publishes its decision with explanations. It is generally accepted in countries where this separation of responsibilities is present that recommendations should not be too specific. In other words the investigators, having pin-pointed safety deficiencies pass them to the regulators: the regulators decide how to implement them. What is not clear to the outside observer who studies the records is which body is responsible for putting the recommendations into the wider context of past accidents and incidents. Since the CAA is, in effect, now part of the JAA, the Joint Airworthiness Authorities of Europe, this matter has become even more complex.

In the USA the National Transportation Safety Board (NTSB) is charged not only with investigating individual accidents but with carrying out special studies often involving the consideration of many accidents. Thus some US safety recommendations made to the Federal Aviation Administration (FAA) quite clearly emanate from accident statistics rather than from a single accident. In the UK the AAIB may refer, as it did following the Tristar bulkhead failure over Manchester, to previous accidents and/or incidents in the main report but this may not always be obvious in the recommendations. As a result we sometimes have the desired result of the CAA in effect expanding a recommendation to cover a wide range of aircraft types and thus implementing it most effectively, while on the other hand the wider implications of a recommendation are sometimes missed because a specific 'fix' is appropriate to the one specific aircraft type of the accident investigation and report.

The problem we are facing is perhaps one created by our own success. The accident rate has for the last few years been at a level that ensures that accidents do not occur sufficiently frequently, particularly to a given aircraft type or to a given airline or even in most countries, for designers, operators and airworthiness authorities to carry a clear idea in their minds of what is really important. Yet unless we assess very carefully indeed where our for ever limited 'safety budget' is best spent we may waste lives as well as money.

So why is the information that is available on past accidents and from safety research not always used? It is easy to answer *'lack of money'* but that is not enough; if all manufacturers and all airlines are called upon to make internationally agreed changes, no one suffers. The passenger will have to pay a little more but will have the benefit of safer flights, after all a few million pounds a year may sound a great deal of money, but shared between a few million passengers it is 'peanuts'. It is not easy to understand why, when authorities in Europe are coming closer and closer together, and closer to the FAA in the USA, agreement cannot now be reached in a reasonable time.

As another example of where it seems that lessons have not been learnt we need look no further than the accident on Manchester airport in the UK on 22 August 1985, now over eleven years ago, in which 55 people died in a US built[1] Boeing 737 (reference 6). This accident is now extremely well known, a great deal of valuable research followed, yet many of the conclusions have been ignored. Even, as in the instance below, where the CAA has been whole-hearted in its endorsement of a finding and recommendation we are still awaiting implementation, it must be repeated, over eleven years after the accident! This is apparently because the CAA is unable to act alone and some of the other European authorities in the JAA do not agree or do not understand the importance of the proposed changes.

It is accepted that some safety systems do have balancing dangers that have to be overcome before implementation so as to ensure that there will indeed be a net benefit. However there can be no such danger in making the minimum width of passageways through cabin bulkheads 30 inches (0.76m), so why are we still waiting? The Manchester report was absolutely clear in its findings that a 22 inch (0.56m) wide passageway through the bulkhead at the front of the passenger cabin was not wide enough. This narrow gap produced a bottleneck that prevented the two forward main exits beyond the bulkhead from being used effectively, yet regulations still allow this gap to be even narrower at 20 inches (0.51m). CAA sponsored research at Cranfield (reference 7) clearly indicated that 30 inches was the minimum acceptable width of such a passageway and a study of relevant emergency evacuations (reference 8) confirmed that evacuation through the front half of the exits and hence through such a passageway was common. A comparison with escape paths and doorway widths in buildings (reference 9) suggested that a minimum width of 0.80m (31.5 inches) would be appropriate. Why is it that even more evidence appears to be needed to get action from the JAA in Europe and from the FAA in the USA?

It may be suggested that a legitimate reason for procrastination in cabin safety issues would be if, due to the

[1] Mentioned since at a safety meeting in Washington in November 1985 it was apparent that very few US people knew of this accident.

measures that **have** been taken, significantly fewer people were being killed and injured in survivable accidents

4. THE PAST TEN YEARS

Unfortunately the promised review of jet and turboprop aircraft accidents since Manchester has not been able to go into as much detail as previous such reviews, for reasons that will be explained later. Furthermore due to the changes in, for example, aircraft types and sizes, it has not been practicable to make exact comparisons (although when Cranfield has the CAA/Airclaims computerised accident data base at its disposal matters should improve considerably). Note that in earlier papers where there was no direct indication that there had been a fire or spilt fuel the probability of there being sufficient damage to provide a real risk of fire was often a matter of judgement. The criterion for inclusion is now based, if there is no other relevant information, on the quoted 'loss percentage'. If this is 100% the accident is included (this figure may be revised downwards when the criteria used in assessing this figure are better understood).

Notwithstanding the shortage of detailed information it can be shown that the proportion of those killed in survivable accidents as opposed to those killed in non-survivable accidents has remained essentially unchanged. For the earliest period considered, 1955 to 1974 some 45% of all fatalities occurred in survivable accidents (reference 10). This decreased to 36% for 1967 to 1986 (reference 11) or to 39% for the pre-Manchester period 1976 to 1985 (reference 2).

For the period 1986 to 1995 the figure has remained at about 36%, however, although for 1989 to 1995 it is 38% and for the three year period 1993 to 1995 it is up to 43%, the variations from year to year do not allow us to be sure that the proportion is in fact increasing, nor of course to claim that it is decreasing! The safest thing to say is that overall it seems to have stayed at around 40%, which is to say that in a year where 1000 are killed in all accidents some 400 will have died in survivable accidents and 600 in non-survivable accidents. It therefore appears that despite the incorporation of some new safety features in some aircraft no improvement is yet apparent. This is disappointing since many people had hoped that changes in cabin materials, better seating arrangements, floor level lighting etc would have reduced the number of fire deaths, and higher strength seating etc would both have reduced the number of impact deaths and also, by reducing the number of incapacitating injuries, have reduced the number of fire deaths as well.

The figure of 1000 fatalities per year has been a convenient yet reasonably accurate round number to use for a remarkably long period, a fact that demonstrates how fatal accident rates have steadily decreased. What is now apparent is that this round figure should increased to 1400, the average over the past four years and with little variation from year to year. Thus the actual numbers killed in survivable accidents, in round figures, now appears to be about 600 per year with the other 800 being killed in non-survivable accidents.

What is clear is that we do still need to make further improvements in order to enhance the chances of surviving an accident as well of course as needing to reduce the probability of having an accident in the first place.

References 10 and, later, 2 attempted to establish how many of the (then) 400 were as a result of the impact and how many were as a result of a fire or, in a few cases, other causes such as drowning. The conclusions were that some 220 died as a result of the impact and 180 as a result of fire, other causes were not discussed but should not be considered negligible. Consequently an objective of the present paper had been to see if these figures had changed as a result of the recommendations and research that followed Manchester. Unfortunately, while some manufactures have been helpful, others, for example Fokker, have been unable to find the time to help as they have in the past, and other available records, including the ICAO data base, provided information on too few accidents for any conclusions to be made concerning cause of death. This last fact would appear to be because many accident investigation agencies still fail to make a complete return to ICAO. In some such cases, but probably not all, this is because the national culture does not permit the time to make an autopsy when a large number of fatalities is involved.

This makes it expedient to take a wider look at the accident statistics and at the route that we might follow to achieve improved cabin safety, though first of all it must be stated that no improvement had been expected since the few safety features that have been introduced in some aircraft have not yet been introduced world-wide. So where do we go from here?

5. A WAY FORWARD?

If we accept, as has the International Society of Air Safety Investigators (ISASI), that the AAIB's report (reference 6) on the B737 accident at Manchester in 1985 was a milestone in the investigation of accidents involving cabin fire, then we must also accept that in the past eleven years we have not travelled far beyond this milestone. As with an actual accident investigation it is all too easy to try to allocate blame, in this case for lack of progress, when we should be looking for the way forward. Perhaps, to conclude the analogy, we have been stuck at cross-roads and need urgently to turn off the road that seems to have made progress virtually impossible.

The underlying spirit behind the Manchester report's recommendations seems to be that there was no single answer but, rather a need to tackle a wide range of problem areas; these were listed and discussed at Sintra in 1989 (reference 2 and others). Many, including the present author, agreed with this wider approach and have emphasised the point that we should tackle fire protection on a broad front rather than concentrate on any one priority issue.

However although research has been conducted into a number of the issues since 1985, there does not appear to have been a unified approach to the problem; some single issues have been almost totally rejected, others have been encouraged for several years only to be dropped later as being not cost effective. It must now be hoped that the recently announced (reference 12) joint US, Canadian and European Aviation Authorities Cabin Safety Research Program, *'described as a totally integrated plan that allows three separate aviation-safety authorities to get the most from their cabin-safety research budgets'* will be able to achieve not just agreement on research programmes but ***action*** based on the results of this research and on that which has gone before it.

Until now one significant reason for our lack of progress could well be that with the very low accident rate that the industry has achieved over the past few decades, ***no*** single safety feature is likely to appear to be cost effective. If one looks at the money needed to be spent each year, usually amounting to many millions of pounds, to save only a few lives, then the argument that it would be better to spent the money elsewhere may seem reasonable. On the other hand if one looks at the additional cost on every ticket required to recover this money, probably only a few pounds on a ticket costing perhaps anywhere between £100 and £500, depending upon how and when purchased, then it may seem ***un***reasonable ***not*** to proceed. But if so, how should we proceed?

One suggestion is that we reconsider the reasons behind our lack of progress, maybe the apparently small benefits to be derived from any one safety feature, the way many research programmes have concentrated on proving and/or improving benefits rather than on minimising the disbenefits of a particular feature, and so on. We should also consider the consequent dangers of suddenly calling for the immediate provision of one or more of the safety features under review before we can be absolutely sure that the benefits ***do*** outweigh the disbenefits.

Perhaps we should seek a new philosophy in which we aim at having a collection of safety features waiting on the shelf until their need is agreed by all concerned. To achieve this we must concentrate R&D on minimising, to an acceptable level, the disbenefits of any feature. Only when this has been achieved should further improvements or further proof of particular benefits be sought.

Examples from safety features already in use are stick pushers and fuel jettison systems. In these the most important issue is to ensure that the chances of inadvertent (and potentially catastrophic) operation are minimised to an acceptable level. That the systems should usually work on the very rare occasions that they are needed is of course highly desirable but several orders of magnitude less important. Similarly it is absolutely essential that doors do not come open in flight, yet they must open readily on the very rare occasions that they are needed for an emergency evacuation following an accident that may well have caused fuselage damage and distortion.

Of those other features relevant to cabin safety several have parallels; Anti-Misting Kerosine, AMK should never cause all engines to stop at the same time; external video systems should never distract the crew and contribute towards causing an accident; water mist systems should not operate inadvertently (or, if they do, they should not jeopardise the aircraft even if they do dampen the passengers); use of smokehoods, whether as instructed or otherwise, should not reduce the number of passengers successfully evacuating an aircraft (note that this is ***not*** the same as saying that they should not increase the time to evacuate); and so on.

Such an approach would, it is suggested, represent a major change in philosophy but it is a fail-safe one in that should a major accident clearly reinforce the need for one or more of these features then there would be no misgivings about too rapid or unconsidered introduction, as may be feared at present.

6. SURVIVABLE ACCIDENTS

6.1 Accidents with deaths by fire

Although accidents, both non-fatal and fatal but where no-one died as a result of the fire, are of major importance to any complete study, it is interesting to look at those where the cause of death **is** known. Table 1 lists these 23 'fire death' accidents and shows how many died by impact and by fire. In addition the two 'percentage' columns show the percentage of those on board who died as a result of the impact, and the percentage of those who survived the impact who subsequently died as a result of the fire. These figures have been derived from a variety of sources and are believed to be correct, however alternative figures with the necessary justification would be welcomed.

It is also important to consider, in **all** survivable accidents, the number of serious injuries. Not only do injuries affect the progress of an evacuation but many, whether due to the impact or to a fire, may result in permanent disabilities.

Date	Aircraft	S.of O.	Dead	S.Inj	M/N	Total	Imp	%I	Fire	%F
850121	L-188	USA	70	1	0	71	43	61	27	96
850415	B-737-200	Thailand	11	0	0	11	2	18	9	100
850802	L-1011-385	USA	134	15	14	163	114	70	20	41
850822	B-737-236	UK	55	15	67	137	0	0	55	40
851212	DC-8-63CF	Canada	256	0	0	256	205	80	51	100
861020	TU-134A	USSR	70	22	2	94	12	13	58	71
870619	Yak-40	USSR	8	12	9	29	5	17	3	13
880227	TU-134	USSR	20	30	1	51	1	2	19	38
880626	A-320	Germany	3	36	97	136	0	0	3	2
880831	B-727-200	USA	14	26	28	68	0	0	14	21
880915	B-737-200	Ethiopia	35	27	42	104	29	28	6	8
890310	F-28-1000	Canada	24	19	26	69	9	13	15	25
890617	IL-62	Germany	21	29	63	113	10	9	11	11
890719	DC-10-10	USA	111	185	0	296	76	26	35	16
900214	A-320	India	92	22	32	146	7	5	85	61
900511	B-737-300	Philippines	8	30	87	125	1	1	7	6
901203	DC-9-14	USA	8	10	26	44	0	0	8	18
910201	B-737	USA	22	10	48	80	1	1	21	27
920120	A-320	France	87	5	4	96	85	89	2	18
920910	F-27 500	Peru	1	24	11	36	0	0	1	3
921221	DC-10-30F	Portugal	56	106	180	342	10	3	46	14
930914	A-320-200	Poland	2	9	59	70	1	1	1	1
940702	DC-9-31	USA	37	16	4	57	32	56	5	20

Table 1 Accidents with deaths by fire, 1985 - 1995

It will be noted that several 'Eastern' built aircraft are included and it may be argued that their cabin materials may be to a different standard (not necessarily lower - look at the record) to those found in 'Western' aircraft. As this aspect has not been investigated the possibility that this could make a difference has to be accepted, however it should also be noted that the aircraft fuel and the baggage, in both the cargo hold and cabin, are likely to dominate the fire and the production of toxic smoke. Thus even the use of totally non-flammable, non-smoke producing cabin materials will not prevent people from dying as a result of a post impact fire. Nevertheless in at least one accident, that to the B727 on 31 August 1988 (reference 13) the investigators were able to conclude that *'a number of lives were saved because the seat cushions were covered with fire blocking material'* but that *'due to a number*

of variables .... an exact number of persons who were saved .... cannot be determined'.

In order to establish in which kind of accident the majority of fire deaths occur reference 1 provided a histogram showing the number of fire deaths in turbine powered aircraft up to the year 1978 plotted against the percentage of those onboard who were killed by the impact. At that time just over 300 had been killed where no-one had died in the impact and another 450 where up to 20% of those onboard died in the impact. In the remaining survivable accidents, more severe in terms of the impact, another 150 died as a result of the fire.

The accidents listed in Table 1 are plotted individually in Figure 1 and Figure 2, by the percentage and by the actual number killed by the impact respectively. It can be seen that, as in the earlier period considered above, over half of these accidents, like the Manchester B737, involve no impact deaths or only a few impact deaths but also that it would be unwise to ignore the others.

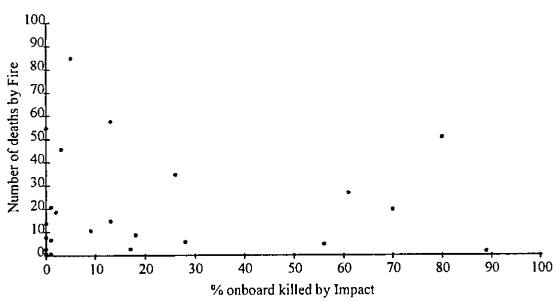

Figure 1 Fire deaths v percentage killed by the Impact

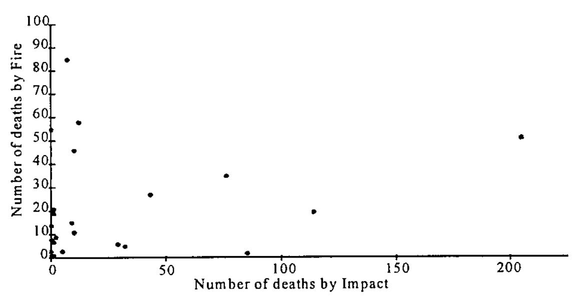

Figure 2 Fire deaths v number killed by the Impact

In addition to these 23 accidents there are some 117 where the cause of death is as yet unknown and as the details from these will obviously affect the results of any analysis this will be pursued no further.

6.2 Categorising survivable accidents

The finding that the majority of fire deaths occur when few if any have died as a result of impact forces can lead to the categorisation of accidents in terms of impact severity but care must be taken when using such data. A rather doubtful philosophy appears to have been adopted by at least some of the leading airworthiness authorities. Perhaps because it is they who have to explain to the media why it is not always possible to produce the 'instant fix' called for and because it is difficult to get across to the media why we have to be so careful before we introduce changes, the authorities have become too defensive. In general of course we must heed Murphy, in that *'every solution breeds new problems'*, but as with the bulkhead gap these new problems are sometimes difficult to substantiate or are merely in the mind.

In reference 11 the scope of cabin safety improvements was sensibly considered under three headings, one non-survivable, involving some 64% of all fatalities and two survivable, involving some 22% and 14% respectively. The difference between the latter two was whether cabin safety improvements *'would be unlikely to make a significant improvement to survival'*, or *'may improve survival'*.

An accident that typified an accident where *'it would be unrealistic to expect that more than a very marginal increase in survival would have resulted from improved fire precautions, evacuation provisions or seating'* was stated to be the DC-10 accident at Sioux City on 19 July 1989. While no-one would disagree that this was a very severe accident, the appropriate details appear in Table 1 and in the above figures, it may be considered that such a categorisation is inappropriately defeatist and consequently counterproductive to our search for improved cabin safety.

There were 296 people on board of whom 111 died, the accident report (reference 14) states that ***'35 passengers died of asphyxia due to smoke inhalation, including 24 without traumatic blunt force injuries.*** *The other fatally injured occupants died of multiple injuries from blunt force impact. Of the remaining 185 persons onboard, 47 sustained serious injuries,* ***125 minor injuries, and 13 were not injured.'*** (author's emphasis).

Although parts of the cabin may have been totally non-survivable it is difficult to accept that only a marginal reduction in the number killed would have resulted from some of the structural and restraint system improvements under consideration. But what of the 24 without injuries who died of asphyxia due to smoke inhalation? To imply that none of the measures discussed before and, more extensively after Manchester could have helped these passengers to survive is quite incomprehensible. Unfortunately such judgements have seriously affected the estimates of the number of lives that might be saved and hence the stated benefits and consequently the opinion of many others. Indeed if many other similar accidents are categorised in the same way then the case for making cabin safety improvements can be diminished or perhaps avoided altogether.

With the breakdown suggested above the maximum number of lives that might be saved, by the whole range of cabin safety features, is only 14% of those killed each year, say 140 out of the nominal 1000. Reference 11 went on to suggest that in practice not all of even this small number could be saved. However on the basis that lives **could** be saved in accidents 'typified' by the Sioux City DC-10, while it is still unreasonable to claim that all, for this period, 360 could be saved, something much closer to this, say at least 250 appear to be within our grasp. If, instead of 360, we use the average number killed in survivable accidents over the three year period 1993 to 1995, approximately 600, then a potential saving of over 400 lives per year is possible.

Since categorising survivable accidents can be useful then a better example of an accident where cabin safety

improvements would have been unlikely to have helped might have been the JAL B747 accident on 12 August 1985 referred to earlier and where just four of the 524 onboard survived. However even here it is conceivable that many more did survive the impact and that had the fire not spread then they too would have survived the accident as a whole, but without autopsies or useful statements from the survivors we will never know for sure. For such severe impacts perhaps only AMK, anti-misting kerosine, might have helped but this is pure speculation.

It has already been mentioned that a study of the data available on survivable accidents will show that many accident investigation agencies continue to ignore the recommendations of ICAO (reference 15) concerning the various reasons for determining and recording the cause of death of each person onboard. This has meant that the cause of death has not been established in a considerable number of possibly important accidents involving both a significant impact and a post impact fire. Of the 117 such fatal but survivable accidents the 21 with at least 50 fatalities are listed in Table 2.

Date	Aircraft	S.of O.	Dead	S.Inj	M/N	Total
850222	An-24	Mali	50	1	0	51
850812	B-747	Japan	520	4	0	524
861212	TU-134	Germany	69	12	0	81
861225	B-737-200	Saudi Arabia	63	31	12	106
870103	B-707-320C	Ivory Coast	50	1	0	51
881019	B-737-200	India	124	5	0	129
890607	DC-8-62	Surinam	177	8	2	187
890727	DC-10-30	Libyan AJ	82	0	117	199
890905	IL-62	Cuba	125	1	0	126
901002	B-737-247	China	82	20	0	102
920731	Yak-42B	China	106	0	20	126
930305	Fokker 100	Macedonia	81	15	1	97
930426	B-737-200	India	55	16	47	118
930723	BAe 146-300	China	55	10	48	113
931120	Yak-42D	Macedonia	115	1	0	116
940426	A-300-622R	Japan	264	7	0	271
940701	F-28-6000	Mauritania	80	9	4	93
941229	B-737-400	Turkey	57	19	0	76
950111	DC-9-10	Colombia	51	1	0	52
951203	B-737-200C	Cameroon	72	6	0	78
951218	L-188 Electra	Angola	141	3	0	144

Table 2 Severe accidents where cause of death is unknown

Any relevant information received pertaining to these accidents would be particularly appreciated.

7. ACCIDENT STATISTICS

7.1 Problems with the statistics of survivable accidents

There are also some peculiar difficulties in actually dealing with accident statistics even when the basic figures are agreed. For example if the recent emphasis in reducing the likelihood of CFIT accidents, virtually all of which are non-survivable, is successful then the result will be that a larger proportion will be killed in survivable accidents. This section therefore goes back over old ground in an attempt to clarify matters.

Any examination of the accident record over the last twenty or thirty years will show that the accident rate to civil transport aircraft has fallen dramatically but a closer look has shown that the fatality rate in those accidents that have still occurred has remained much the same. We have it seems succeeded in considerably reducing the chances of having an accident but not the chances of dying should we be unlucky enough to be involved in an accident. This is a critical reason behind the need to increase our understanding of the crashworthiness and survival aspects of accidents.

So far, so good; one can divide the accidents as suggested, the only difficulty being to agree a definition of a 'survivable accident'. Although several definitions exist the one that seems most useful is 'an accident in which at least one person survives the impact'. In a few accidents where all on board have died, some have survived the impact only to die as a result of the post-impact fire. Such accidents are survivable by the definition but can only be so attributed if the cause of death is known, two accidents of this nature appear in Table 1. It is therefore unfortunate that the researcher sometimes still has difficulty in tracking down the information necessary to establish this extremely important point and that sometimes the information has not been recorded.

There have inevitably been a few accidents where one or more persons have survived the impact apparently quite miraculously and there is the reasonable temptation to make a judgement that such accidents should be classified as non-survivable. This has been resisted by the author, or rather the temptation has been rejected partly to keep matters simple and partly on the basis that it would be surprising if there were not also a few accidents where all died but where more detailed information would indicate that some did in fact survive the impact. Luckily such borderline accidents seem to be very rare and thus do not affect the overall numbers to any great extent.

The real difficulties start when we try to read significance into the numbers. The shortcomings of looking only at fatal accidents are important. In short many clearly significant differences are totally obscured, the most obvious being the presence or not of a post-impact fire (reference 10). Considering fatal accidents alone and out of context can lead to some quite ridiculous conclusions. The finding that roughly the same percentage of those on board died in accidents with a post-impact fire as when impact was the only killer possible should alert one to the problem. Bringing into the equation appropriate **non**-fatal accidents produces sensible results which can lead to sensible conclusions and useful recommendations.

7.2 When is an improvement not an improvement?

A further problem is that a genuine improvement in survivability can make the record appear worse and of course, vice versa. If this is not already clear then the reader is invited to consider two consecutive years each with 10 identical fatal but survivable accidents. If, for example, we save one in every ten killed in each of the 10 accidents then the overall fatality rate is reduced by 10%. If on the other hand the same number of lives is saved but this time all from one accident, making this one non-fatal, then we have only 9

fatal accidents with which to divide the fatalities and the apparent overall fatality rate will have remained unchanged.

If we consider an extreme case then it is hoped that the argument becomes totally obvious. Take two accidents each with 100 on board. In one accident only one dies, in the other 99, and the average fatality rate is 50%. If we save that one person in the first accident then the fatality rate, now based solely on the one remaining fatal accident, **increases** to 99%. If we fail to save the one survivor in the other accident then this becomes non-survivable and we are left with a fatality rate in the survivable accidents of 1%. These are clearly major distortions of the figures and illustrate the dangers of looking at fatal, survivable accidents alone and out of context.

Another distortion can arise if we do not treat with care any combination of accidents involving greatly differing numbers of people. Again considering an extreme example should make the point. Suppose our two accidents, to the same aircraft type, are such that in one 10 people are killed out of 20 on board, while in the other 190 are killed out of 380 on board. Each kills 50% of those on board. Does a safety measure that saves **all 10** in one accident count for more or less than one that saves **15** of the 190 in the other? The numbers say one thing but the real relative merits must depend on whether it is likely that, had the first aircraft had 380 onboard, all or most of **these** would have been saved. It is by no means easy to make such a judgement even when an accident has been investigated thoroughly!

7.3 New safety features

Another difficult problem (reference 2) that we have to deal with when trying to use past accidents as a guide to the potential benefits of some new safety feature is that other improvements may have been incorporated since some of these past accidents occurred. It then becomes necessary that we try to assess how many lives might have been saved had these other improvements been installed earlier, before trying to assess how many **more** lives might have been saved by the new feature. In one accident we can only save a life once! For such calculations to be convincing it must first be shown that there has been a genuine reduction in the fatality rate in relevant survivable accidents and then that this reduction may reasonably be attributed to some particular previous safety feature or features. This technique is still in its infancy and, largely because some relevant accidents were not investigated in sufficient detail, the results of early attempts to state 'what would have happened if .....' have been unavoidably controversial.

The current position is that until we can establish the causes of death in a reasonable proportion of the accidents that have occurred during the nineties we cannot assess accurately whether any changes have occurred. Nevertheless such information as we do have suggests that little, if anything has changed and that action on cabin safety matters is still urgently required.

8. CONCLUSIONS

Many accident investigation agencies do not establish and/or report the cause of death in survivable accidents. This seriously curtails research into the means of preventing such fatalities.

Since the Manchester B737 accident in 1985 and the safety recommendations and research that followed, there has been no noticeable improvement to the overall record of survivable accidents.

Some cabin safety improvements that have been introduced are expected to lead to a reduction in fatalities but so far there is insufficient detailed information available to establish if they have had any beneficial effect.

Many other recommendations made following the Manchester accident have not been implemented, over eleven years after the accident.

The overall safety record is sufficiently good to make it very unlikely that any particular safety feature will appear to be cost-effective. Consequently, if progress is to be made, a new way is needed of dealing with such safety features.

Emphasis should be placed on minimising the disbenefits of potential safety features in order to optimise the net benefit.

The world's airworthiness authorities are getting together to co-ordinate cabin safety matters. They should be encouraged to act upon relevant research already completed as well as to initiate new research. They should examine past accident statistics with care and develop and use appropriate cross checks in order to avoid distortions. They should seek to establish ways of speeding up all routes leading to the implementation of significant improvements in cabin safety throughout the world.

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DISCUSSION - PAPER NO. 2

W.B. de Wolf (Question)

It seems clear now that an aisle width of 20 inches is unacceptable for an efficient cabin evacuation. For sufficient width in a Boeing 737 a 5-abreast layout is required instead of 6-abreast. Do you think that the consequences of such a change are accepted by the public and/or by the airline companies?

F. Taylor - Author (Response)

I am not aware of any evidence that supports the claim that the aisle width between the seats is unacceptable, therefore I do not agree that the number of seats should be reduced. Survivors' accounts and trials suggest that people climb over the seats and that the bottleneck is the bulkhead. It is the minimum width of passageways through bulkheads that needs to be increased from 20 inches to 30 inches. I am sorry if my paper does not make this clear.

A REVIEW OF RECENT CIVIL AIR TRANSPORT ACCIDENTS/INCIDENTS AND THEIR FIRE SAFETY IMPLICATIONS

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1. ABSTRACT

This paper presents a brief summary of recent civil air transport accidents and major incidents involving fire. It updates the paper "Investigation and Characteristics of Major Fire Related Accidents in Civil Air Transports Over the Past Ten Years". A more detailed review of selected accidents/incidents is presented including their link to safety improvements made to-date in fire resistant materials and their impact on improved passenger survivability and the need for improvements in aircraft systems, such as oxygen, hydraulic and electrical, to further improve survivability. Research and Development to reduce aircraft fire fatalities is discussed and justified using accident/incident data. The paper discusses the problem of Halon replacement. Accident/incident data is used to show the need to choose replacement agents that can perform well against real aircraft fires. The need for realistic test methods is discussed. The paper concludes that additional improvements in passenger fire survivability are needed and attainable.

2. INTRODUCTION

Over the past ten years the Federal Aviation Administration (FAA) and most other aviation authorities worldwide have implemented numerous modifications to aircraft fire safety standards. Those modifications have vastly improved fire safety in transport aviation. Those modifications include the following:

The Seat Cushion "Fire Blocking" Rule. This rule requires that all cabin seat cushions in transport aircraft meet a large oil burner test. The result of this rule change was that most seat cushions were "fire blocked". The term fire blocking refers to encapsulating the foam with a very fire resistant material. The fire blocker is usually over urethane foam and under the outer dress cover. The fire blocking materials presently available cannot be dyed. Therefore, they are not used as outer covers. Until recently, urethane foam, the only foam meeting airline requirements, could not be made fire resistant enough without a large, and unacceptable, increase in weight. The effects of this rule have been documented in accident investigations and in one case, Delta 727 in Dallas, Texas, August 31, 1988, it was cited by investigators as having provided a longer evacuation time, thus, saving many lives.

Floor Level Lighting Rule. This is a requirement for emergency lighting near the floor in an aircraft. As a result, most airlines have installed floor track lighting (light strips on the floor).

Low Heat/Smoke Release Panel Rule. This is a requirement for the large surface material in an aircraft cabin (ceiling, sidewall, stowage bins, partitions, etc.), and is required for newly manufactured or totally refurbished aircraft. This is also referred to as the "OSU Rule" because of the test method required. This rule forced the airframe manufacturers to upgrade most of the materials used in aircraft interiors.

Cabin Fire Extinguisher Rule. A requirement of transport aircraft to carry at least two Halon 1211 extinguishers. This requirement may have resulted in saving a Delta L1011 from a catastrophic inflight fire over the North Atlantic on March 17, 1991.

Lavatory Smoke Detection/Extinguishment Rule. This rule requires smoke detectors in all transport aircraft lavatories as well as a fixed extinguisher (known as a potty bottle) in all lavatory trash receptacles. The main job of these systems is the protection against smokers in the lavatory.

Radiant Heat Resistant Evacuation Slide Requirement. This was a change to the Technical Standard Order (TSO) that contained the requirements for the emergency evacuation slides. The change incorporated a radiant heat test for slide material designed to improve the ability of the slide to resist the heat from a large fuel fire nearby.

Cargo Compartment Rules. There have been three major rule changes effecting cargo compartments on transport category aircraft. The first was a change to newly certificated aircraft only. It reduced the allowable size of a class "D" compartment to 1000 cubic feet, and imposed a new test method for cargo liners, seams, joints, and fastening systems. The second rule change was a retroactive rule requiring the modification of class "C" and "D" compartments. This rule has lead to the removal of Kevlar and Nomex liners, the redesign of some fixtures and fastening systems, and new methods for patching damaged liners. The third rule change was an AD changing the requirements for class "B" (Combi) compartments.

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

It should be noted that the greatest improvements in fire safety have been gained in the area of materials flammability upgrading.

Safety improvements are judged by their expected benefit versus their cost. Since future benefit is most often based on past accident experience, it is very important to have enough information about past accidents as a basis for that judgment. In evaluating a safety improvement, a wide range of accident scenarios must be studied, making sure that improvement in some scenarios is not a detriment in others.

TABLE 1
Civil Transport Aircraft Accidents (1987-1996) with Fire-Related Deaths or Destruction of the Aircraft By Fire

	Date	Carrier	Place of Accident	Type of Aircraft	Number of Occupants	Number of Fatalities
1.	4/Apr/87	Garuda	Medan	DC-9	45	28
2.	5/Aug/87	Lan Chile	Santiago	B-737	33	2
3.	16/Aug/87	Northwest	Detroit	DC-9	155	154
4.	15/Nov/87	Continental	Denver	DC-9	82	28
5.	28/Nov/87	South African	Indian Ocean	B-747	161	161
6.	26/Jun/88	Air France	Habsheim	A-320	136	3
7.	31/Aug/88	Delta	Dallas	B-727	108	14
8.	15/Sep/88	Ethiopian	Bahir, Dar	B-737	104	35
9.	17/Oct/88	Uganda	Rome	B-707	57	32
10.	25/Oct/88	Aero Peru	Juliaca	F-28	89	12
11.	3/Feb/89	Burma	Rangoon	F-27	28	26
12.	10/Mar/89	Air Ontario	Dryden	F-28	86	24
13.	19/Jul/89	United	Sioux City	DC-10	286	111
14.	14/Feb/90	Indian	Bangalore	A-320	146	92
15.	11/May/90	Philippines	Manila	B-737	119	8
16.	3/Dec/90	Northwest	Detroit	DC-9	44	8
17.	1/Feb/91	USAir	Los Angeles	B-737	89	22
18.	11/Jul/91	Nationair	Jeddah	DC-8	261	261
19.	30/Jul/92	TWA	New York	L-1011	292	0
20.	21/Dec/92	Martinair	Faro, Portugal	DC-10	340	56
21.	02/Jul/94	USAir	Charlotte	DC-9-31	57	37
22.	08/Jun/95	ValuJet	Atlanta	DC-9-32	62	0
23.	11/May/96	ValuJet	Miami	DC-9	109	109
24.	17/Jul/96	TWA	New York	B-747	230	230

3. ACCIDENTS AND INCIDENTS

The following is an update of selected transport aircraft fire related accidents and important incidents for the years 1987 through September 1996.

3.1 ACCIDENTS

1. South African Airlines, November 28, 1987.[2] A South African Airlines 747 "Combi" (passengers and cargo on the main deck) experienced an inflight fire while flying over the Indian Ocean. The plane crashed into the Indian Ocean and all on board were killed. The investigation concluded that the most probable cause was a fire in the class "B" main deck cargo compartment, which grew out of control, and caused the destruction of the aircraft.

As a result of this accident, the FAA has issued an Airworthiness Directive that requires fire safety design and firefighting improvements in class "B" compartments.

2. Air France, June 26, 1988.[3,4] The aircraft crashed into trees while attempting a "touch and go". A fire immediately broke out and penetrated the cabin. Evacuation began shortly thereafter via the left side. The clothing on some of the passengers caught fire. Everyone on board was able to evacuate with the exception of a handicapped boy, a little girl, and a woman who had made it to an exit but, apparently, returned into the cabin to help the girl.

Fire blocked seats are credited with extending survival time and saving numerous lives.

3. Delta Airlines, August 31, 1988. A Delta Airlines 727 crashed on takeoff from the Dallas/Fort Worth

Airport. The aircraft suffered severe structural damage as it slid to a stop approximately 3,000 feet from the end of the runway. The right wing was ripped from the fuselage, causing a large fuel spill; and the aft two cargo doors opened and a large section of the fuselage above and forward of the main aft cargo door was torn away. A large circumferential break also occurred just aft of the cockpit. A large fuel fire separated the aft section from the rest of the fuselage at the aft break. All but two of the fatalities were trapped in the aft section. The doors in that area could not be opened from inside because of the angle at which that portion of the fuselage was resting. The evacuation in the forward portion of the cabin was through the fuselage and the two left over-wing exits. It was estimated that evacuation time from aircraft stop until the last passenger was out was 4 minutes and 20 seconds. This was based on crash rescue and firefighting services recordings. There were two passengers in the forward cabin that succumbed to the effects of the fire.

This accident is of extreme interest since it was the first survivable accident involving fire following the implementation of the floor proximity and fire blocking rules. Initial indications from passenger interviews were that no one utilized the floor lighting in egress of the aircraft. That could be expected since the accident occurred during daylight and large breaks in the fuselage provided visible means out of the aircraft. From remains of the cabin materials and passenger accounts of the evacuation, it could be concluded that fire blocking seats did extend the survival time in the forward portion of the cabin. Although an exact additional escape time or added number of survivors that could be attributed to fire blocking cannot be determined, an estimate utilizing past test data was made. It was estimated 1 minute and 30 seconds of added survival time was provided in this accident due to the incorporation of fire blocking. That equated to a life savings of 37 passengers.

4. Philippine Airlines, May 11, 1990. The aircraft was being towed from its stand to an area where the engines could be started. During the pre-start sequence, fuel vapor in the empty center wing tank was ignited. The resulting explosion ripped the floor open and upwards into the cabin, breaking the legs of some passengers in the process, and a fireball erupted into the cabin. The force of the explosion fractured the wing internally and fuel from the wing tanks fed back into the center section area where a very large intense fuel fire developed in the cabin.

The fuselage was intact, however, the cabin was disrupted by the explosion. All fatalities were due to the fire and explosion.

This accident points out that even with non-combustible materials in a cabin, a large internal fire can occur.

5. Northwest, December 3, 1990. A B-727 on its takeoff roll collided with a DC-9 in fog. The right wing of the B-727 penetrated the right side of the DC-9 fuselage, cutting into the flight deck and forward service door. It sliced the length of the cabin ejecting fuel from the damaged wing tip. On hitting the right engine of the DC-9, a fireball erupted from the rear of the aircraft, and fire traversed forward throughout the cabin.

The wing of the B-727 caused fatal blunt force trauma to the occupants of the cabin. The fire fatalities occurred in the aft tailcone area towards the ventral escape door. The operating mechanism for this door failed, and the passengers and one cabin attendant were trapped by the intense fire that had by this time developed in the cabin.

The interior fire was caused by fuel sprayed into the cabin, causing a rapidly developing cabin fire.

6. USAir, February 1, 1991. A Boeing 737-300, collided with a Fairchild Metroliner while the B-737 airplane was landing on runway 27 left at Los Angeles International Airport, Los Angeles, California. The Metroliner was positioned on the same runway, at intersection 45, awaiting clearance for takeoff.

The B-737 remained largely intact as a result of the collision with the Metroliner. The fuselage belly was ripped open and the cabin floor displaced. The B-737 veered off the runway and into a building where the cockpit top and left sides were crushed.

All 10 passengers and two crew members aboard the Metroliner and 20 passengers and 2 crew members aboard the B-737 were fatally injured.

After the aircraft came to rest it quickly filled with smoke, reducing passenger visibility. Some passengers reported using the emergency floor path lighting to find the rear exit. Survival time in the aircraft was estimated to be about 90 seconds. A majority of the fatalities were found lined up at overwing exits.

The investigation revealed that the high pressure oxygen line next to the crew oxygen bottle in the lower area of the fuselage had been ruptured by the impact and that the release of oxygen into the forward cabin area had greatly accelerated the fire, sharply reducing survival time.

7. Nation Air DC-8, Jeddah, Saudi Arabia, July 11, 1991. This aircraft experienced burst tires and wheel failures on the main landing gear during takeoff. The takeoff was not aborted and the burning landing gear was retracted after the airplane was airborne. The fire spread up into the cabin as the crew declared an emergency and attempted to return to the airport. The airplane crashed approximately one mile short of the runway, killing all occupants. The inflight cabin fire was burning so intensely that burned cabin interior materials and bodies were falling from the airplane before the first impact point.

8. TWA, July 30, 1992. A TWA L-1011 aborted a takeoff, landed hard and ruptured a wing fuel tank. A large fuel fire engulfed the aft portion of the aircraft. Fire and smoke entered the cabin through the aft doors during the evacuation. All 292 occupants exited through 3 forward exits in approximately 2 minutes.

Additional "non-working" flight attendants aided in the evacuation.

9. ValuJet DC-9, June 18, 1995. The airplane experienced an uncontained compressor disk failure during the takeoff roll in Atlanta, GA. Sections of the disk ruptured the number 2 engine fuel line and an interior and exterior fire resulted. All of the occupants from the sparsely loaded airplane evacuated safely. The most serious injury was to the flight attendant sitting in the aft jumpseat who suffered burns and shrapnel wounds. The airplane was destroyed by fire.

The accident illustrates another source for cabin fires and the importance of rapid evacuation.

10. ValuJet DC-9, near Miami, FL, May 11, 1996. The investigation of this accident is still ongoing, but what is known so far is that a fire originated in the forward cargo compartment shortly after takeoff. The crew declared an emergency and attempted to return to Miami. The airplane crashed approximately 10 miles from the airport killing all 110 occupants. A large quantity of sodium chlorate oxygen generators were in the forward cargo compartment. They had not been properly packaged or labeled.

11. TWA B-747, near Long Island, NY, July 17,1996. An explosion destroyed the aircraft inflight, with no survivors. The ongoing investigation is looking at the possibility of a bomb, missile or mechanical failure that caused the explosion of the center fuel tank.

The outcome of the investigation may have design and safety implication for fuel tanks on transport aircraft.

3.2 INCIDENTS

In many cases, the difference between an accident and an incident is pure luck. The probability of the next aircraft accident having similarities to a given past incident are the same as the probability of similarities to a given past accident. It is, therefore, extremely important that all fire incidents with potential extensive damage to the aircraft or life-threatening be investigated, analyzed, and understood. It should be noted that because of the limited damage in some incidents much more information can be learned than in an accident. The following are examples of incidents that have led to research and/or safety improvements in aircraft:

1. Delta, Salt Lake City. Maintenance was being performed on the oxygen system in the forward electrical compartment as the aircraft was being pre boarded by passengers. As the B-727 aircraft was being reactivated a violent fire erupted. Smoke and fire quickly spread up into the first class area of the aircraft. The few passengers on board were quickly led out of the aft of the aircraft by flight attendants. The flight engineer was the last evacuee and was forced to crawl to escape the smoke and heat. He exited and overwing hatch. The estimated survival time was 30 to 45 seconds. The oxygen fed fire destroyed the aircraft.

2. American West, Tucson. A B-737 experienced hydraulic problems inflight. The aircraft made an emergency landing and then lost all hydraulic power. The investigation showed that a frayed electrical cable had arced to a hydraulic line causing a small hole in the line. The hydraulic fire mist was ignited by the arc and continued to burn. The subsequent fire ruptured a return line on the hydraulic system and shorted the wiring to the standby pipe.

Subsequent testing showed that fire resistant hydraulic fluid mist may continue to burn after the ignition is removed if the misting occurs in a confined area.

3. LTU, Dusseldorf, Germany. While performing maintenance on the L-1011 aircraft in a hangar the vapors from a cleaning solvent ignited. The aircraft was totally destroyed by the fire.

It was discovered that the propellant for the non-combustible solvent was a replacement for the chlorofluorocarbon (CFC) and was highly inflammable.

4. Delta, North Atlantic. An inflight fire occurred in an L-1011 while on a flight over the North Atlantic. Flames were seen coming from a floor grill near the left aft end of the cabin. Flight attendants used 3 halon and one water extinguisher to extinguish the fire.

Examination of the area showed considerable burn damage; however, it was localized because the fire was extinguished before it could spread. The return air grill, some interior sidewall paneling, several square feet of the cabin floor, and insulation blankets above and below the cabin floor level were severely burn damaged. A passenger's coat that was placed on the floor caught fire as did a few smaller personal items. Beneath the cabin floor the main generator cables from the auxiliary power unit were also severely burn damaged. The cargo liner sidewall and ceiling panel in the area showed signs of fire with some of the resin burnt out and the panels sooted on the outside.

It should be noted that the original Nomex cargo liners had been replaced by fiberglass liners meeting the oil burner requirements. Had the liners been Nomex, it is probable that the fire would have burnt "over" through into the C3 cargo compartment.

This incident points out the need for extinguishing agents capable of penetrating into hidden areas and extinguishing inaccessible fires.

5. Indian Airlines, New Delhi, India. During maintenance of a B-737, the passenger oxygen system was deployed for a check, and an oxygen fed fire erupted in the vicinity of the pressure controller. The fire was controlled after doing structural damage to the aircraft with the use of outside fire extinguishers.

6. American Airlines, Nashville. An inflight cargo fire occurred in a DC-9 due to the carriage of hazardous materials. This incident points out the potential problem of the carriage of unlawful hazardous materials in cargo bays.

7. SAS MD-87, Copenhagen, Denmark. Just after touch down, a flight attendant in the aft of the aircraft noticed ceiling work lights in the galley area getting very bright

and then go out. This was followed by an electrical smell and then white smoke from the ceiling area. As the aircraft pulled to the gate, black smoke began to fill the aft portion of the aircraft. Passengers were evacuated and a fire developed and spread rapidly. The fire damage was extensive in the aft of the aircraft, including burning a hole through the fuselage skin. The investigation indicated two wires shorted to each other and ground causing an arc which started the fire.

8. Dominicana 727, Santo Domingo, Dominican Republic. September 4, 1993. Approximately fifteen minutes into a thirty minute flight from San Juan to Santo Domingo, a flight attendant noticed a flight attendant call button lit for the aft lavatory. She checked the lavatory and saw smoke inside. The airplane landed at Santo Domingo and the passengers exited normally through the L1 door as the cabin began to fill with smoke. The flight crew requested a mechanic with a fire extinguisher to check the lavatory. The mechanic opened the ventral stairs and saw fire that he judged to be too big to attempt to fight with a hand held extinguisher. The airplane was destroyed by fire. The fire was determined to have originated in the area of the aft lavatory but the cause was never found.

9. Intercontinental DC-9, Barranquilla, Columbia, March 3, 1995. A fire ignited in the area of the flush pump motor in the aft lavatory just after the APU was started and the airplane was being prepared for the first flight of the day. The fire had burned out of the lavatory before the crew became aware of it. The airplane was destroyed by fire.

4. THE FUTURE OF AIRCRAFT FIRE SAFETY

4.1 Materials Upgrade

Most of the material flammability upgrading to date has been aimed at the postcrash fire, a fire entering into the aircraft from a large external fuel fire and spreading on the interior cabin materials. Although there are still some areas such as the seat components, curtains, and transparent fixtures that should be studied to determine if upgrading of standards would increase safety, full scale tests on seat components have indicated that incremental changes would lead to little safety improvement. Therefore, near term, only small safety improvement could be expected from cabin material flammability upgrades for the postcrash fire scenario. Long range R&D will center on highly fire resistant (almost non-combustible) materials.

Although the materials in the cabin have been upgraded and fire safety greatly improved, little has been done to the materials that are the most likely to be involved in an inflight fire. These are hidden materials, materials such as behind the sidwall, over the ceiling, and below the floor.

Recent incidents and tests indicate that the thermal acoustical insulation bagging material is a greater factor in flame spread than previously thought. FAA R&D is presently focusing on the adequacy of the current flammability requirement in that area.

4.2 Burnthrough Requirements

In some accidents, British Airtours 737, Manchester, United Kingdom, August 22, 1986, for example, it was determined by the investigators that the external fire entered into the cabin by burning or melting through the fuselage.

A joint FAA, CAA research program is underway to evaluate potential burnthrough improvement.

4.3 Systems Approach

A major step has been taken in upgrading material standards, but further improvements in that area will not solve the entire problem (cabin furnishings do not affect the smoke, heat and flames entering the cabin from the external fuel fire). Also, there are potential fire hazards from other fuel sources on board, such as hydraulic fluid, passenger carry-on materials, and oxygen. What can be done to further improve fire survivability? Have we gone far enough?

Examination of past accidents and full scale testing suggests that improvement to oxygen and hydraulic systems could improve both inflight and postcrash fire safety. Oxygen systems have been the cause of aircraft fires (ATA DC-10 in Chicago, August 1986, Delta 727 in Salt Lake City, October 1989 and preliminary data indicates ValuJet DC9 near Miami, May,1996) and have contributed to the severity of postcrash fires (USAir 737 in Los Angeles, February 1991). For the near term, methods of containment (such as flow restrictors, fuses, or solid oxygen generating systems) should be explored. The final answer may be an oxygen nitrogen separation system. These systems (OBOGS - Onboard Oxygen Generating System) are presently available, however, with an extreme weight penalty. Long term R&D is needed to reduce the weight output ratio.

Even with the improvements to present systems there is still the problem of the fuel fire. How can the hazards of the external fuel fire spreading into the passenger cabin be reduced? One method that shows great promise is a cabin water spray system. The system would consist of a fixed quantity of water stored on board the aircraft that would be discharged from nozzles throughout the cabin in the event of a postcrash fire. Testing has shown the system to be extremely effective, reducing the hazards in a cabin and extending survival time for most postcrash fire scenarios. Although , at present, the cost / benefit ration for a cabin system is unacceptable for rule making, at combined cabin-cargo system may have some promises.

5. ADDITIONAL PROBLEMS

With the banning of ozone depleting CFC's, additional problems are developing in the aircraft industry. Those problems are two-fold. First, CFC's are no longer being used as propellants in aerosol cans. The replacement propellants are butane and propane, which are highly

flammable. This presents a major problem in cargo compartment fire protection. Solutions are to redesign some cargo compartments or redesign aerosol cans. Second, the halon extinguishing agents used in transport aircraft (Halon 1301 and 1211) are also ozone-depleting chemicals and are no longer being manufactured, by international agreement. There is a need to effectively recycle halons and to develop new non-ozone depleting agents and the means of demonstrating equivalent fire protection to the halons in aircraft applications.

6. CONCLUSION

There are still major improvements that can be made in aircraft fire safety; however, a systems approach is needed to accomplish them.

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DISCUSSION - PAPER NO. 3

R.E. Eichenbach (Question)

Passenger oxygen systems have been involved in possibly increasing fatalities in ground or near ground level accidents. Do you know or have data on number of lives saved by on-board passenger oxygen systems (excluding handheld for medical emergencies)?

R.G. Hill - Author/Speaker (Response)

I know of no available data or studies on the subject.

E.R. Galea (Question)

Concerning the TWA B747 disaster, you suggested that the investigation has so far found that the central fuel tank exploded. However, so far no evidence supports the theories that (a) a bomb exploded, (b) a missile struck the aircraft, or (c) a spark in the fuel tank initiated the explosion. If these are eventually ruled out, what other means could have caused the tank to explode?

R.G. Hill - Author/Speaker (Response)

At present, none of those three have been ruled out. I know of no other ignition sources being considered.

P. Kotsiopouls (Question)

Refering to the TWA Flight 800 accident at Long Island, you mentioned that the central fuel tank was found to have exploded, but there is no evidence up to now that this explosion has been due to a bomb, missile or arc. Can you think of any other event that may have caused this explosion?

R.G. Hill - Author/Speaker (Response)

No. These are the three ignition sources that are being investigated.

A Computer-based Simulation and Risk-Assessment Model for Investigation of Airliner Fire Safety

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1. ABSTRACT

A computer simulation model has been developed to investigate fire safety issues in commercial passenger aircraft operations. The aim of the work has been to create a computer-based analysis tool that generates representative aircraft accident scenarios and then simulates their outcome in terms of passenger injuries and fatalities. The details of the accident scenarios are formulated to closely match the type of events that are known to have occurred in aircraft accidents over the last 40 years. This information has been obtained by compiling a database and undertaking detailed analysis of approximately 200 airliner fire accidents. In addition to utilising historical data, the modelling work has incorporated many of the key findings obtained from experimental research undertaken by the world's air safety community.

The unique feature of the simulation process is that all critical aspects of the accident scenario have been analysed and catered for in the formative stages of the programme development. This has enabled complex effects, such as cabin crash disruption, impact trauma injuries, fire spread, smoke incapacitation and passenger evacuation to be simulated in a balanced and integrated manner. The work is intended to further the general appreciation and understanding of the complex events that lead to fatalities in aircraft fire accidents. This is achieved by analysing all contributory factors that are likely to arise in real fire accident scenarios and undertaking quantitative risk assessment through the use of novel simulation methods. Future developments will enable the undertaking of a systematic exploration and appraisal of the effectiveness of both current and future aircraft fire safety policies.

2. INTRODUCTION

Modern commercial air transport provides a safe, economic and convenient form of travel over long distances. However, inevitably, accidents do occur and they can often result in high rates of mortality in aircraft occupants. Most incidents involve fire, which can expose potential survivors to a lethal thermo-toxic environment and contribute significantly to overall fatalities. The nature of the fire survival problem can differ considerably from accident to accident. For example, a night-time crash occurring a large distance off airport constitutes a quite dissimilar predicament to, say, an uncontained engine failure on takeoff, or an in-flight cargo fire. As well as their potential diversity, aircraft fires also tend to involve many complex, highly interactive and dynamic phenomena. These attributes can make it difficult to integrate knowledge obtained from past events or plan purposeful research programmes to investigate issues of concern in aircraft fire safety. Similarly, it is also far from straightforward to perform a satisfactory analysis of the effectiveness of current or proposed new safety measures[1]. In addition to purely objective considerations, those involved in the field of aircraft safety also deal with a highly emotive subject matter. This is occasionally highlighted by the vociferous but often poorly informed media coverage and public lobbying that can occur in the immediate aftermath of a major accident. The formulation of safety policy must also take account of the highly cost sensitive nature of the air transport industry, together with possible political implications and the limitations imposed by historical precedence[2].

Faced with these challenges, those committed to minimising the hazards of fire in aircraft possess only limited resources with which to work from. Detailed historical information is readily available from the investigation of past accidents. When carefully assimilated, this data can provide a reasonable indication of the problems likely to be encountered in future incidents. However, the information is usually qualitative in nature and may often be unreliable or incomplete. This can lead to contradictory indications being obtained from the study of individual accidents in isolation. It is therefore necessary to relate historical data from many incidents in order to obtain a reliable appreciation of past events[3].

When detailed information is required about a specific aspect of fire safety, it is often possible to undertake some form of experimental research programme. These studies can provide reliable quantitative information to enable the optimisation of particular safety parameters in an experimental environment. However, if the results of such work are to be of real value, care must be taken to ensure that test conditions adequately represent those likely to be encountered in actual aircraft accidents. The fulfilment of this requirement can make some experiments very expensive to perform and thus severely restrict the number of times that they can be undertaken. In the case of aircraft evacuation trials, it is obviously not possible to incorporate the dehabilitating effects of real fires and impact trauma injuries to any realistic extent. A range of analytical modelling techniques have also been used to compliment experimental studies in specific aspects of aircraft safety. In particular, computer-based methods have been developed in the areas of fire simulation, impact analysis and occupant evacuation modelling. Although some notable results have been obtained, much progress still remains to be made in these areas.

3. A HOLISTIC APPROACH TO SAFETY ANALYSIS

Those involved in the exploration and analysis of fire safety in commercial aircraft possess a need to integrate a large body of

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information, containing many diverse and often seemingly incompatible types of data. In spite of the quantity of information available, appreciable gaps in understanding still remain in many areas[4]. Thus scientists, engineers and policy makers can routinely be forced to take decisions involving significant factors that lie outside their own areas of expertise and without access to suitable sources of information to refer to. Greater levels of accountability in the policy formulation process also means that there is increasingly a need to provide clear quantitative justification for many of the conclusions reached in matters of public safety[5]. The addressing of these difficulties clearly requires that the maximum utilisation is made of all available information sources in any decision making process.

The use of a holistic approach in the analysis of aircraft safety has always been difficult to implement. The sheer complexity of aircraft accidents necessitates that research be undertaken by specialists in particular aspects of safety. The knowledge provided by these sources is usually of a high level and can often be of a very involved nature or time-consuming to assimilate. Consequently, information obtained from specialised branches of research can be difficult to integrate, both from across different disciplines and with historical data obtained from past accidents. Thus, there may be a danger that significant research findings may go unappreciated or not be fully utilised to improve the safety of air transport operations.

One potential solution to these kind of problems is to make use of some form of knowledge framework or decision support tool[6]. This can serve to combine the many sources of information on safety matters in an explicit manner. The complexity of events typically encountered in aircraft accidents clearly suggest that any such tool would need to involve computer simulation methods in order to provide an adequate level of analysis. Also, *all* relevant features of an incident would need to be considered, such as fire development, passenger evacuation and the effects of any crash impact. This might then enable findings from more specialised branches of safety research to be integrated within a complete accident analysis for the first time. In the longer term, the development of these techniques could potentially yield a tool capable of supporting a systematic risk assessment analysis of key issues in aircraft fire safety.

The primary challenge in constructing such an accident analysis tool is in dealing with the sheer quantity, diversity and intricacy of the information available. Obviously, in order to create a tractable computer model, it is necessary to make many simplifications and approximations in the analysis process. In some instances, gaps in knowledge have to be bridged, often with little more than the application of educated guesswork. Practitioners of holistic modelling techniques also leave themselves open to criticism from specialists, who can occasionally perceive their intellectual contributions to have been trivialised or devalued in some way. In most cases, these difficulties can be overcome by carefully documenting and justifying the internal workings and assumptions inherent in the analysis being undertaken. Care must also be taken to ensure that the capabilities of these types of tools are not overstated or misrepresented in any way. The primary role of such models should be seen as promoting a more general awareness and understanding of complicated phenomena, rather than providing definitive answers to extremely challenging problems at the push of a button.

This paper describes a prototype of such a tool for the purpose of investigating key issues in airliner fire safety.

4. THE STUDY OF PAST ACCIDENTS

The construction of the computer model has been performed in conjunction with the undertaking of a detailed survey of airliner fire accidents and incidents that have occurred over the last forty years. The data survey began 12 months before any computer programming was started. This has allowed the form and scope of the simulation modelling to be matched with the diverse range of accident types that might be expected to occur in the future. Modelling techniques have also been tailored to take optimal advantage of the relative strengths of historical and scientific information, as judged appropriate. The initial phase of the survey involved the construction of a database containing approximately 2000 individual incidents, based on CAA data[7]. This was then used to arrive at more manageable total of 217 accidents to be targeted for more detailed research. Each of these consisted of a survivable (or partially survivable) incident involving a turbine-engined airliner, in which fire posed a significant threat to passenger survival. The information obtained on these incidents has been drawn from accident reports, databases of other researchers, national aviation authority publications, aircraft manufacturers and private sources.

In addition to data gathering, the survey has included a systematic analysis of the type of scenario and the significance of salient details present in each event. The incidents have been classified in terms of aircraft type, the occurrence and severity of any crash, together with the initiation, growth and properties of the fire. Each of the accident fires has been classified into one of four categories. These are *impact*, *burnthrough*, *internal* and *external* fires, respectively. It was found that the type of fire present usually provided a reasonable indication as to the nature of the fire survival problem faced by aircraft occupants. The occurrence of a significant crash impact and the presence of structural disruption to the fuselage also appeared to play a substantial role in many of the cases studied. The relative frequencies of crash impacts, fuselage damage and the four types of fire are shown in Figure 1. Note how the plotting of these statistics in

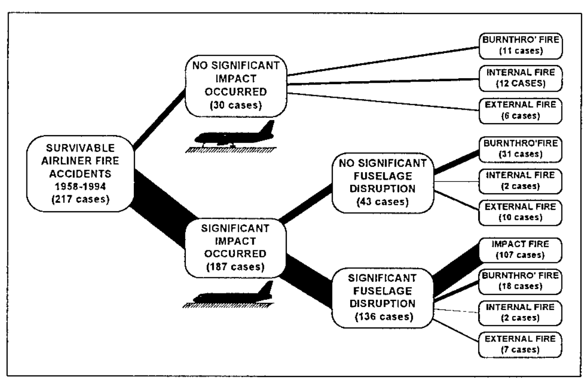

Figure 1: Accident Scenario Tree

the form of an event tree allows all of the accidents to be classified into one of ten categories. The predominant type of incident appears to involve an impact fire, following a crash and with the presence of significant fuselage disruption.

Much attention was also paid to ascertaining details of the passenger evacuation process in each of the accidents studied.

Particular emphasis was placed on noting the description of the cabin thermo-toxic environment resulting from the fires and the effect that this appeared to have had on the aircrafts' occupants. Other miscellaneous items of information were also recorded. These included prevailing weather conditions, the nature and location of the accident site, and the role of intervention of emergency fire fighting and rescue services.

One task of particular relevance in the study of aircraft fire accidents was determining what proportion of fatalities had actually resulted from the effects of fire, as opposed to impact injuries or other causes. A breakdown of our best estimates for these figures is provided in Figure 2. The first point to note is

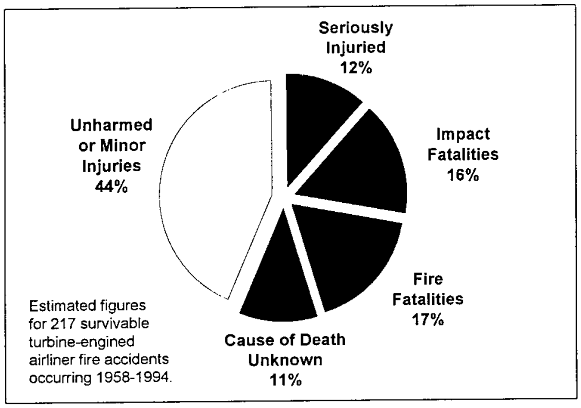

Figure 2: Aircraft Fire Accident Casualties

that, for the accidents studied, the proportion of occupant fatalities resulting from fire and impact were almost equal. Secondly, it can be seen that only 12% of people involved in these accidents were seriously injured. This implies of that 88% of occupants were either in a position to escape from their aircraft relatively quickly, or else they did not survive. These figures underline the critical role that rapid evacuation of passengers has played in many past aircraft accidents.

5. THE "TOTAL SCENARIO"

The information gathered about airliner fire accidents indicated that, in many cases, the outcome (i.e. the lethality) of a given incident was not just a function of the fire and the passenger evacuation *per se*. In general, it was observed that a wide range of factors often determine the evolution and subsequent outcome of aircraft accidents. These influences can exhibit a high degree of interaction in many cases and in combination they form the "Total Scenario" present in an accident. Typically, these factors might include the weather, time of day, local terrain, intervention of emergency services, the aircraft's fuel load and cabin configuration, together with the actions of passengers and aircraft crew members.

The implementation of a satisfactory risk assessment model thus required detailed prior knowledge of the Total Scenario that was likely to be present in an accident. Many aspects of this information could possibly be highly significant in determining fire casualties. Given that some were of a very fundamental nature, provision needed to be made for their incorporation within the model at an early stage of it's development. Consider, for example, the role that structural disruption of a fuselage can play in allowing fire to ingress immediately into a passenger cabin. It was found that the degree of fuselage damage present in an accident correlated more closely with fire fatalities than any other parameter that was tested. This implied that fuselage structural integrity might be just as relevant in the overall analysis as fire size, the role of emergency services or speed of passenger evacuation. Consequently, much effort was directed towards incorporating the effects of fuselage impact damage into the fire and evacuation modelling. Figure 3 illustrates a typical example of

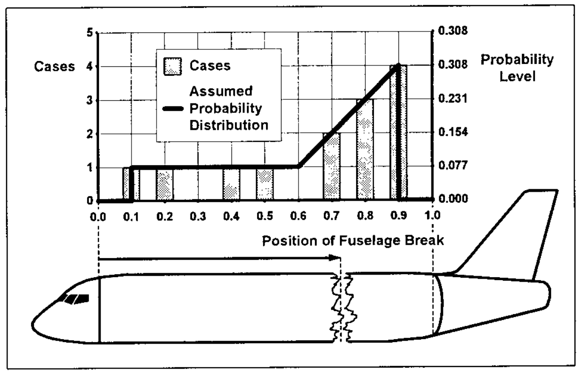

Figure 3: Probability Distribution for the Position of a Single Fuselage Break

these activities. In approximately 13% of the accidents analysed, the aircraft's fuselage had broken into two or more sections and high rates of fire fatalities had often resulted. Therefore, it might be beneficial to obtain a probability distribution for determining whereabouts along the length of the passenger cabin breakages were likely to occur. It can be seen, even with the low number of cases available for analysis, that fuselage dislocations are more frequently encountered towards the rear of the cabin area.

Analyses of this kind were performed on many different aspects of the accidents studied. Much of this data was relatively straightforward to derive from accident reports or other sources and it could often provide important insights about the true nature of past accidents. The type of information required to define a scenario could often be very elementary. For example, answers needed to be obtained to questions such as will the wind blow smoke inwards if the exit is opened?, or, are the passengers likely to be injured and evacuating in darkness?, or, what is the probability of the fuselage being ruptured or upside down?, etc. If basic questions like these were not addressed, then the resulting analysis would not be applicable to a representative cross section of accident scenarios. Consequently the risk assessment model could never be capable of providing a balanced analysis of real incidents and would be of little relevance to the study of safety policies.

Therefore, one of the primary aims of the work has been to construct a computer simulation model that is able to generate a realistic spectrum of aircraft fire accident scenarios. The provision of this capability has been based on results obtained from a comprehensive survey and analysis of past accident data. Each scenario description generated by the model consists of three main groups of information:-

1. *General Scenario*. This includes information about the aircraft type and it's cabin layout, the prevailing weather, phase of flight, airport distance, availability of emergency services, etc.
2. *Impact Effects*. These consist of structural damage to the aircraft's fuselage, fuel spillage, fuselage break-up, cabin

disruption, jamming or obstruction of exits, occupant injuries, etc.

3. *Fire type*. Specifically the size, location and nature of the fire or fires present. Four distinct types of fire have been defined, namely, Crash, Internal, Burn-through and External fires. The accident fire type is a function of both the *General Scenario* and the *Impact Effects*.

6. UTILISATION OF EXPERIMENTAL RESEARCH

In addition to the analysis of past accidents, a further input to the simulation work comprised the findings of experimental and theoretical researchers. Results were utilised from many of the various disciplines associated with aircraft fire safety. For example, the areas covered included aircraft crash and fire testing, materials combustion, fire modelling, toxicology and passenger evacuation. The results of such experimental work have only been incorporated within the simulation model when they have been shown to be consistent with real events, or failing that, there was no other information available. Frequently, difficulties were encountered in attempting to apply some of the data from these sources. This was because, sometimes, experimental procedures or assumptions used in an analysis would only be valid in a small proportion of real accidents. Alternatively, some types of scientific investigation yielded results that were undoubtedly valuable in a different context, but were simply too specialised for incorporation into the holistic type of analysis being undertaken. Examples of the latter included materials fire testing, computational fluid dynamics (CFD) modelling of fires and occupant impact testing.

7. FIRE MODELLING

Much effort has been expended by the world's fire safety community into creating sophisticated computer codes for predicting the growth, spread and effects of fires. However, at present, most of these CFD methods are unsuited for integration within a more widely based simulation programme, due to their numerical complexity and requirement for precisely specified input data, which can often be difficult to obtain[8]. Arguably, for the provisional analysis of aircraft accidents, we only require the gross features of a fire and estimates of a few key parameters at an approximate level of accuracy. Thus it was decided to adopt an empirical approach to the modelling of aircraft fires. Many of the techniques utilised in the analysis have been established in other branches of fire safety engineering, most notably for quantifying the characteristics of open pool fires[9].

The empirical fire model used is suited to dealing with crash, burn-through and external fire scenarios, which were found to occur in over 90% of accidents studied. At the time of writing, internal fires (occurring within the pressurised section of the fuselage and rarely involving the aircraft's fuel supply) were not dealt with adequately. They almost certainly require the use of a second type of fire model, capable of representing the effects of combustion in closed compartments. However, the increasing rarity of severe internal fires makes the implementation of a second fire model a relatively low priority. The approach taken has been to interpret past accident fires in terms of an "equivalent pool fire" area. The spatial characteristics of the fires, i.e. their size, shape and location are represented by 2-D analytical functions that vary with time. These have been derived from the detailed study of 72 accident fires for which it has been possible to obtain an adequate level of information. For example, Figure 4

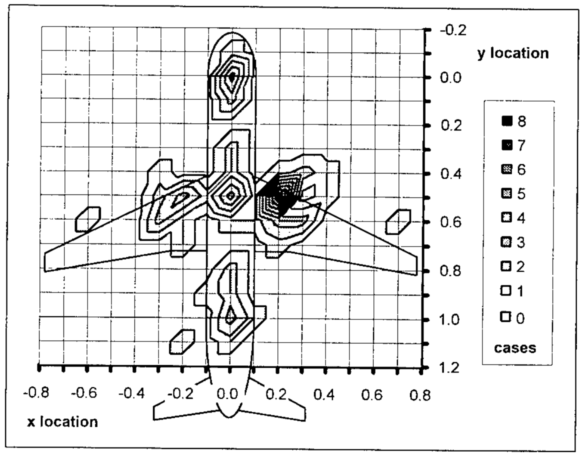

Figure 4: Probability Contour Map for Position of Fire Starting Point

illustrates the probability density distribution that has been derived for determining the starting position of a fire. This was obtained by plotting the estimated starting points of the 72 accident fires in units based on the cabin length of the aircraft type involved. Rate of fire growth, together with levels of smoke and toxic gas production are modelled with simple differential equations. These are very difficult to calibrate to any degree of accuracy, but coefficients have been set to yield results that are generally consistent with those observed in real accident fires. It should be noted that the effects of fire-fighting intervention have not been modelled explicitly, but they are inherent in the fire size probability distribution being used. The use of a 2-D representation of the cabin thermo-toxic environment means that stratification effects can only be dealt with in a comparatively crude manner. As a stratification mechanism has yet to be added to the fire model, cabin conditions are assumed to be represented at chest height, i.e. 1.5m above floor level. Provision has also been made throughout the analysis programme to model simultaneously the upper cabins of double-deck aircraft.

The spread of heat and fire combustion products through the aircraft cabin are represented at an approximate level with the use of numerical diffusion and flow methods. The latter are based upon an analytical airflow solution for the cabin (or

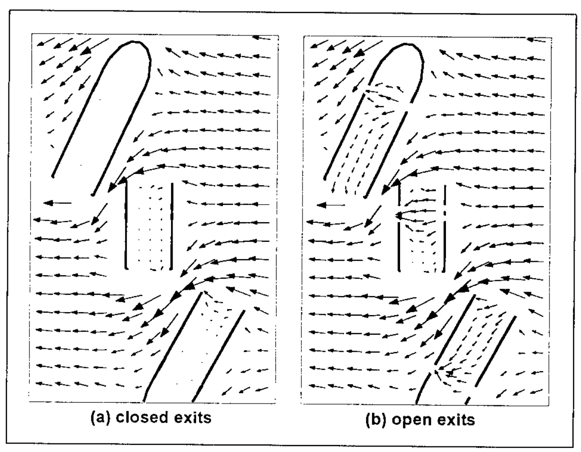

Figure 5: Analytical Airflow Model

cabin wreckage), obtained with a 2-D panel method[10]. Two example flow solutions are shown in Figure 5. The first diagram provides a basic indication of airflow in and around the wreckage of an aircraft with all exits closed. Note that the wind direction is from the right and that the internal flow vectors have been magnified for clarity. The second diagram illustrates the changes in cabin airflow that might be expected to result when all exits have been opened. Although this type of approach may only provide a very approximate indication of a true three dimensional flow field, it can be calculated on a modern desktop computer in less than a second. The flow model is capable of dealing automatically with any cabin geometry and arbitrary distributions of aircraft wreckage. Also, the method is efficient enough to allow cabin airflow to be updated as each exit is opened or when significant portions of a fuselage are destroyed by fire.

The resulting thermo-toxic environment represents little more than an approximate indication of the cabin conditions that might be encountered in an accident. However, given the qualitative nature of our knowledge about human physiological and behavioural response to fires, the use of a more elaborate analysis is probably unjustifiable in the present context. The fire and thermo-toxic modelling analysis should be regarded as first attempt to encapsulate the basic properties and dynamic characteristics of aircraft fires in a form suitable for wide-ranging risk assessment activities.

8. MODELLING OF OCCUPANT EVACUATION

The purpose of the accident simulation model is to investigate the factors that might influence the lethality of airliner fire accidents. With the exception of deaths resulting from any crash impact, the survivability of an incident is determined by the ability of the aircraft occupants to escape from the effects of fire. This egress process is approximated by the evacuation sub-model of the simulation tool.

The evacuation of occupants is computed on an array of cells that are coded to represent the layout of the aircraft's cabin. Thus, individual cells might depict passenger seats, an aisle, galley units, exits, cabin partitions, etc. Passengers leave their seats and move towards the exits according to a set of rules. Typical cabin configurations for all major passenger aircraft types currently in service have been prepared. This represents a total of approximately 80 different layouts. New cabin configurations can be defined with the use of a simple programming language.

Passengers traverse the cabin grid in steps of one cell at a time. The use of a varying time-step simulation clock ensures that evacuees may move at arbitrary speeds. The evacuation process is event driven, so for example, a fast individual may well undertake two or three moves in the time period that a slower person moves only a single cell. A given cell may only be occupied by one person at a time. However, resolution of the cabin grid (0.15 - 0.20m) is sufficient to ensure that co-operative overtaking is possible in narrow aisles. Compressibility of passenger queues and maintenance of personal body spaces can also be represented.

The escape tactics of passengers are to move towards the nearest exit. Simple refinements have been added to make the nearest exit less attractive if it has yet to be opened or if there is a large queue of people waiting to use it. Thus passengers may swap their exit choices if nearby exits are opened or queues form for their chosen exit. Individual passengers possess different personal attributes, including reaction time, movement speed, narcosis and irritant levels, etc. These attribute sets can be expanded, if passenger behaviour models are developed further. In addition to it's primary use in the analysis of accidents, the egress model can be used to investigate certification type evacuations, as shown in Figure 6. The diagram illustrates the certification seating configuration of the Boeing 757-200 aircraft and passenger positions part way through a run. Results achieved in this type of analysis are comparable to those reported by other researchers working in the area[11].

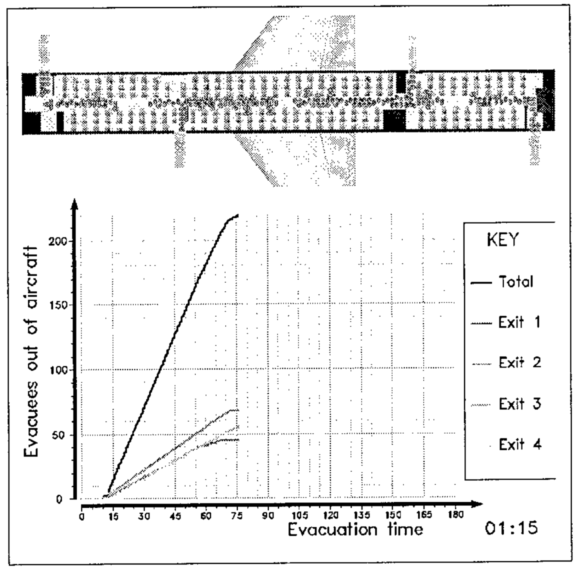

Figure 6: B-757 Certification Evacuation

However, the primary achievement of the evacuation modelling has been to fully integrate the analysis with the other parts of the accident simulation. Thus, for example, when an exit is opened during an accident evacuation, smoke or flames might enter the cabin and deter evacuees from using it. Correspondingly, passengers have been made less likely to open a given exit if fire is present outside. Simple probability distributions can be used to generate exit jamming or opening delays. These distributions have been derived from information gathered on exit usage in the accident survey work and from the findings of other researchers[12]. At present exits are operated by passengers and no attempt has been made to represent the presence of cabin crew in the simulation, although this could potentially be of importance[13]. Exit flow rates have been calibrated to match those achieved in aircraft certification and experimental research trials[14]. However, it should be noted that these are not necessarily representative of rates achieved in actual accidents.

A major challenge in the modelling of aircraft accident evacuations lies with the inclusion of the effects of occupant impact trauma injuries and thermo-toxic incapacitation. Provision has been made for incorporating these effects in the evacuation model with the use of injury and Fractional Effective Dose (FED) factors for each of the aircraft's occupants. The values of both these parameters may vary between 0.0 and 1.0, representing perfect health and complete incapacitation respectively.

Impact trauma injury rates, together with associated levels of cabin disruption have been estimated for past accidents in cases where sufficiently detailed information had been obtained. This process simply involved the assignment of occupant injury and cabin disruption ratings to each incident, on a subjective scale of 1 to 5. This information was processed to create approximate probability distributions that relate to the overall severity of the crash being simulated. These are then used to factor the movement rates of individual passengers and degrade ease of movement though certain sections of a cabin. Although this approach to representing the effects of impact in the evacuation of aircraft is obviously extremely basic, it serves to slow down evacuation rates to levels that are generally consistent with those observed in past accidents.

The thermo-toxic incapacitation of passengers has been based on standard FED methods(15). These are used to factor speeds of evacuee movement in a linear fashion. Thus occupants are slowed down and eventually stopped by the cumulative effects of narcotics, irritants, heat and smoke present in the local cabin environment.

The progress and the final outcome of the evacuation are illustrated with a graphical display (see Figure 6). Full details of exit opening times, exit usage and evacuation rate can also be provided.

9. USE OF THE ANALYSIS MODEL

Although the modelling work is still at the developmental stage, it possible to demonstrate all of the features described. Much work remains to be performed in detailing and calibrating many parts of the analysis to a more satisfactory level. However, it is clearly apparent that degree of functionality provided in the model will enable a wide range of analyses to be undertaken in the near future.

Some of the areas that might be addressed include:

- The relative effectiveness of Type III overwing exits in different accident scenarios
- The potential effects of introducing passenger protective breathing equipment
- The role of airport emergency services in aircraft accidents
- The optimisation of passenger evacuation strategies, including the role played by old and disabled travellers
- Fire safety issues inherent in the introduction of new Very Large Aircraft designs

Preliminary studies have already been performed in the area of the final item. Figure 7 shows the process of evacuation

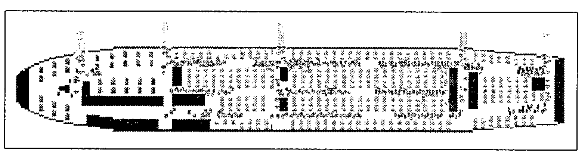

Figure 7: Evacuation of a VLA Design

from a provisional Boeing Very Large Aircraft (VLA) design. Note that the width of the lower cabin in this class of aircraft will almost certainly require the use of three aisles. Work has been undertaken to explore different strategies for directing passengers originating from the central aisle. Also, significant numbers of passengers on the second deck may attempt to look for stairways rather than use upper level escape slides. The certification of aircraft in this category can be expected to present many new challenges in matters of fire and cabin safety in the future.

10. EXAMPLE RESULTS

The nature of the work outlined in this paper makes it difficult to provide results in a concise format. The analysis model is still undergoing development and thus full scale Monte Carlo testing has yet to begin. Most of the trial work that has been performed to date has involved the calibration and linking of individual sub-models. With the exception of occupant evacuation, this does yield data in a form suitable for presentation. However, use of the tool for the purpose of performing certification type passenger evacuation trials has already been undertaken. Some results of these tests are presented in Table 1.

Aircraft Type	Seats	Actual Time	Model Time
A320	179	79.0s	85.0s
A321	224	-	81.2s
B-757	219	73.5	77.8s
B-737-800	189	-	91.8s

Table 1: Evacuation Trial Timings

Note how variations in the model times compare reasonably well with results obtained in actual certification tests of the aircraft. The over estimation of timings is due mainly to two factors. Firstly, cabin crew are not present to open emergency exits for passengers. Secondly, passenger exit choice in the simulated evacuation leads to overloading of some exits. In the real trials, passengers are often re-directed to make optimum use of all available exits.

An example showing the use of the simulation model in the analysis of a single aircraft accident is given in the Appendix to this paper.

11. CONCLUSION

The accident simulation and analysis model that has been briefly described is still undergoing continuous development. However, even at this stage, it is being used to perform exploratory studies and risk assessment in key areas of airliner fire safety. Topics that may be addressed in the future include the optimisation of emergency exit placement and utilisation, the effectiveness of airport fire fighting services and the fire-safety analysis of future Very Large Aircraft designs. The examination of these issues can be undertaken in a systematic manner, with a tool based on a foundation of historical accident data and a wide selection of relevant experimental fire safety studies.

The focus of the research effort remains with the development of a programme that can be used to analyse aircraft fire accident scenarios in as complete and balanced a manner as possible. The objective is to produce an integrated tool with the potential to aid design, risk assessment and policy exploration studies in the field of airliner fire safety.

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APPENDIX - ANATOMY OF AN AIRCRAFT FIRE ACCIDENT

A.1 Introduction

This Appendix illustrates the simulation analysis of a survivable airliner fire accident. Admittedly the modelling work still an ongoing process and thus parts of the analysis still remain comparatively basic. However, it will be seen that significant results are already being obtained and that the aim of providing a totally integrated risk assessment tool is well within sight. Furthermore, a substantial quantity of information has been gathered and is awaiting incorporation into the model.

It is obviously impossible to define a single "average" accident scenario for the purpose of demonstrating the simulation model. Therefore, details of the incident under consideration have been carefully chosen to be generally representative those encountered in many accidents. It should also be pointed out that some details of the accident have been pre-set or even omitted for presentation purposes. In particular, deaths, injuries and cabin disruption resulting from impact forces have not been included, for reasons of clarity. It will also be noted that wind conditions have been made particularly severe.

Finally, the entire rationale of the work has been to provide a computer-based tool for the systematic "Monte Carlo" analysis of many hundreds of accidents. Past events have shown us that it can be dangerous to plan and act on the basis of the most recent or more "typical" accident scenarios. The outcome of individual incidents can be heavily influenced by small variations in critical parameters. Thus, it is necessary to identify and assess the range of potentialities that could actually occur in the future, rather than planning exclusively on the basis of past events. Results obtained from the work in the future will therefore be reported in the form of probability distributions, in addition to the examination of discrete test cases, such as that provided here.

A.2 The Accident Scenario

The accident simulation portrayed here involves an Airbus A320 class of aircraft, carrying a full load of 150 passengers. The airliner's two-class cabin configuration and the location of exits are shown in Figure A1. The accident was projected

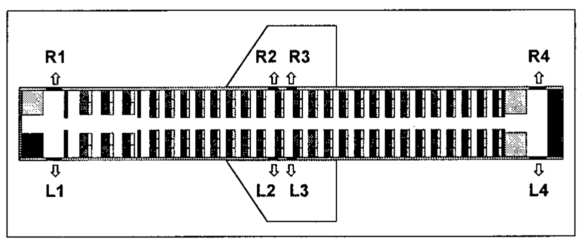
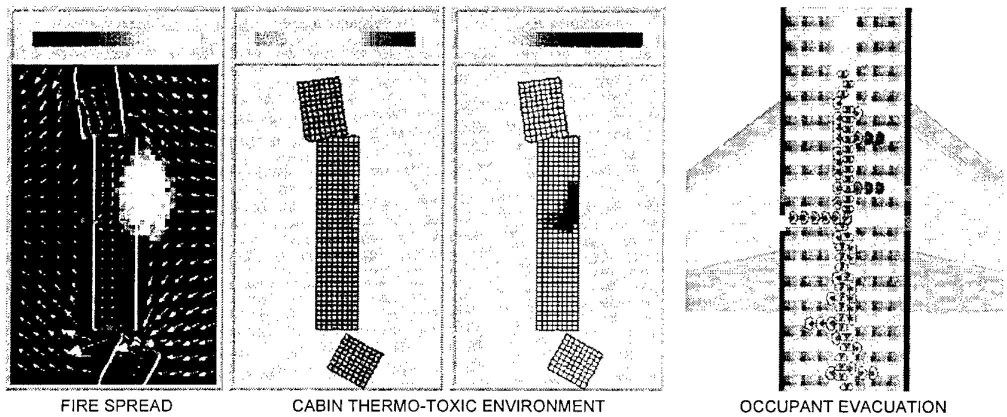


Figure A1: A320 Cabin Configuration

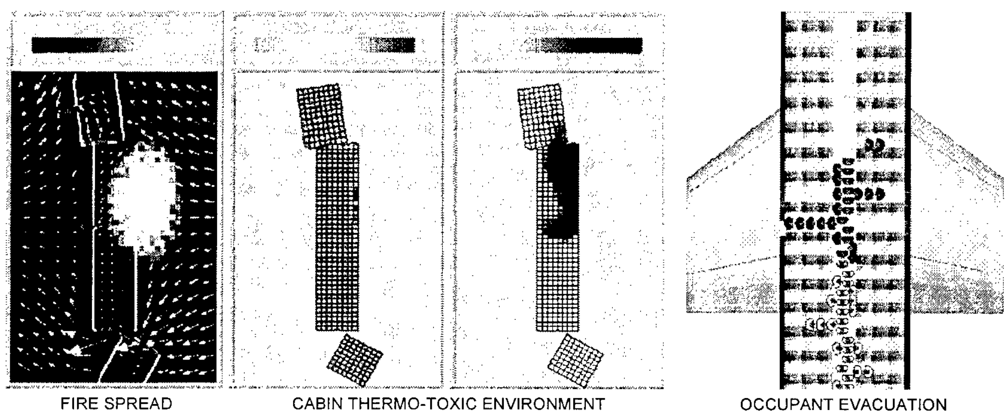
to have occurred after takeoff and the aircraft came to a stop on open ground, 0.6 nautical miles from the airport. The model's scenario generator determined that the crash landing involved a substantial impact, leaving the aircraft's fuselage broken in two places and with gross fuel spillage occurring. The breaks were positioned at the first class/economy cabin divide (seat row 4) and at near the rear of the cabin (row 27). An intense fire erupted in the starboard wing root area immediately after impact.

The analysis presented here focuses on the central cabin, where all the fire fatalities were projected to have occurred. Four overwing exits were available for use in this part of the aircraft. Those on the right hand side (R2 and R3) were blocked by fire and the forward left overwing exit (L2) was not opened. The forward fuselage break was obscured by debris resulting from the displacement of the forward cabin section. Thus, the only means of escape for 132 of the aircraft's occupants was via the L3 exit or through the second fuselage breakage.



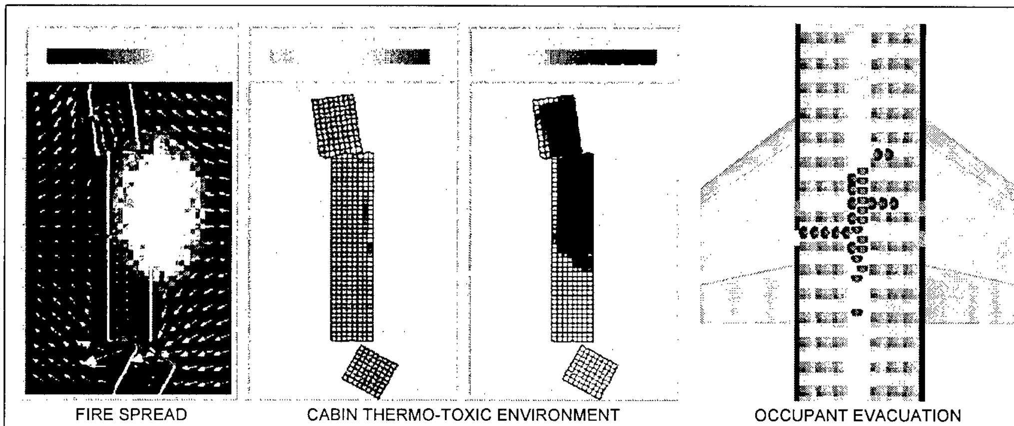
The fire has burnt through into the cabin within 60 seconds. Passengers nearest the fire turn black as they are overcome by heat, smoke and toxic fumes. The L3 exit flow rate is decreasing in the rapidly reducing visibility and many people are becoming trapped in the centre of the cabin.

Figure A2: Fire Penetration into Passenger Cabin (75s After Impact)



Much of the central cabin is now engulfed in smoke. 48 passengers have managed to escape via the single overwing exit, but 26 others are now unconscious. The remainder are faced by a wall of smoke and turn around in an attempt to make their way towards the rear fuselage break.

Figure A3: Exit Blocked by Incapacitated Passengers (120s After Impact)



The front half of the cabin is now unsurvivable and dense smoke is pouring from the L1 and L3 exits. 28 of the aircraft's occupants have lost their lives in the fire within the space of 3 minutes. The first 5 passengers to be overcome failed even to leave their seat rows.

Figure A4: Last Survivor Escapes from the Aircraft (180s After Impact)

A.3 Projected Outcome of the Incident

The progression of the accident simulation is illustrated in Figures A2-A4. Cabin conditions and the positions of passengers are shown at 75, 120 and 180 seconds after the occurrence of the crash. The time history of the evacuation from the aircraft wreckage is shown in Figure A5.

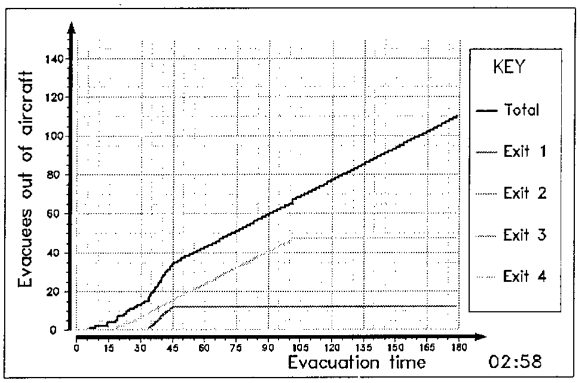


Figure A5: Evacuation History

The 18 passengers in the forward cabin were able to escape safely through the L1 exit within 45s. In the main section of wreckage, the L3 exit became blocked by dense smoke and falling passengers after 102 seconds. Then, the only means of escape available for remaining survivors was the rear fuselage break. It can be seen that 28 of the 150 passengers aboard the aircraft were overcome by the effects of the fire. Total evacuation time was 3 minutes and 17 seconds.

It should be noted that the inclusion of occupant crash injuries and cabin disruption would have slowed the rate of evacuation considerably. This may then have lead to a greater number of fire fatalities occurring, even if significant numbers of deaths had resulted from the effects of impact forces.

DISCUSSION - PAPER NO. 4

E.R. Galea (Comment)

As you point out in your Paper, the danger with the holistic approach is that - by necessity - it tends to oversimplify various aspects of the phenomena under investigation. This appears to be the case in this model - in particular the fire model. Your analysis is restricted to 2-D panel models. Research into fire simulation (see Paper No. 7) suggests that the fire dynamics is extremely 3-D, turbulent and dynamic. Studies using 2-D models have not only produced different values in key fire parameters such as temperature & smoke concentration compared with full 3-D models but, more importantly, they have produced very different trends in behaviour, in some cases missing some important behaviour altogether. Adopting this 2-D approach can therefore be counter-productive and misleading. Furthermore, a 2-D approach does not allow the proper representation of cabin obstacles such as seats, which have a profound effect on fire propagation.

P. Macey - Author/Speaker (Response)

Yes, we accept that our analysis over-simplifies many aspects of aircraft fires. This was our intention. The fire model was developed after the detailed examination of 72 aircraft fires and careful analysis of full-scale experimental fire test results.

We are very satisfied with the results being obtained; for the vast majority of accident scenarios, we can estimate all important cabin environment parameters at an acceptable level of accuracy in real time. Perhaps we should bear in mind that our knowledge about the thermo-toxic incapacitation of humans is comparatively crude. Thus, arguably, for the purpose of undertaking wide-ranging fire survivability analyses, approximate estimates of the cabin environment will suffice.

Instead, we have diverted our attention towards dealing with a fully representative range of realistic fire scenarios and integrating the fire modelling with other parts of the analysis. Now that this has been achieved, the move to a 3-D fire model is a logical next step, and we anticipate that this will be performed in the next 12 months.

E.R. Galea (Question)

Studies into human behaviour in real aircraft accidents (see for example Paper No. 36) strongly support the observation that passengers will (1) jump over seats in order to reach an exit, (2) have a tendency to follow others, especially if in family groups, i.e. associative group behaviour, and (3) move through smoke layers. How does the evacuation component deal with these issues? Furthermore, research suggests that the mobility and travel speed of people moving through smoke decreases. Does the evacuation model cater for this, and on what is this decrease in travel speed based?

P. Macey - Author/Speaker (Response)

Our evacuation model includes capabilities such as jumping over seat backs, uncooperative overtaking, maintaining of personal space, group behaviour and sideways movement by evacuees. The task of programming these types of mechanisms is comparatively straightforward - however the real issue is how do we calibrate them: i.e. how, why and when do they occur?

For example, consider the climbing of passengers over seat backs. We know that it took place at Manchester and is frequently encountered in some types of evacuation trials (Paper, ref. #14). However, our historical research suggests that seat climbing has probably occurred in only a very small proportion of past accidents. This may be due to lower levels of passenger agility (stemming from impact injuries & demographic considerations) and less aisle crowding (caused by delayed passenger responses, lower seating densities, lower load factors, etc...) generally present in the incidents we have studied. Consequently, we are unable to calibrate our seat jumping function with any degree of certainty and have chosen not to activate it in the simulations undertaken to date. The situation is similar for our passenger overtaking and spacing models. However, sideways movement of passengers and an associative behaviour function have been employed as a matter of routine. The latter coordinates the movements of small groups of passengers, for example, to head for the same exit and to move forward together.

Passenger movement through smoke layers is obviously a critically important aspect of our simulation. We utilise data published by Jin (listed in Paper Ref. # 15), which suggests that movement in irritant smoke reduces to that in darkness (i.e.: crawling?) at optical densities of 0.2/m. Thus, we assume that passengers are brought to a standstill in a linear fashion as densities approach 0.3/m. Please note that these values are necessarily approximate given the nature of the experiments.

Numerical Simulations of Aircraft Cabin Fire Suppression

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ABSTRACT

This paper deals with the modelling, using Computational Fluid Dynamics (CFD) models, of the suppression of aircraft cabin fires using a waterspray system. Combustion was computed using a multi-reaction combustion model and the waterspray trajectories were calculated using a transient Lagrangian model. A fire with a heat release rate of 50 kW was simulated using a pan containing heptane and used to determine the suppression effectiveness of a fine waterspray system. The watersprays were generated using a single nozzle located near the ceiling of the cabin right above the pan.

The results showed that, with adequate water mass flow rate, the waterspray system was able to extinguish the assumed fire. With lower mass flow rates, the fire was not extinguished, however, the watersprays were able to cool the hot gases and to maintain survivable conditions in the cabin in terms of temperature. It is important to note, however, that the modelled fire had a fixed area and fire spread was not considered. Allowing the fire to spread to a larger area may result in different extinguishment characteristics.

This paper demonstrates that it is possible to use CFD models to simulate the effectiveness of waterspray systems in suppressing aircraft cabin fires. Such models are useful tools to complement real tests and can be used to evaluate the impact of the various parameters on suppression effectiveness and cabin conditions.

INTRODUCTION

Life threatening aircraft fires are generally post-crash fires or in-flight fires. Post-crash fires are usually initiated outside the cabin, due to fuel spills, and then may gain entry into the cabin via openings in the fuselage caused by the crash or open doors. In-flight fires usually occur in accessible areas inside the cabin, such as toilets or galleys or in hidden areas behind panels. In-flight fires are caused either by humans or electrical malfunctions. References [1-4] indicate that between the years 1964 and 1984 approximately 1,000 passengers lost their lives as a result of in-flight fires.

Most airport fire services are well equipped and well trained to be able to intervene and effectively deal with a post-crash external fire. The ability to deal with in-flight fires, however, is limited. Improvements made so far to address this problem are limited to regulating the flammability of aircraft internal materials and to installing smoke detectors and hand extinguishers [5]. Although these measures improved the safety of the passengers in the event of a fire, accidents such as the June 7, 1983 Air Canada Flight 797 [6] indicate that better means for fire suppression or fire control may be required. In this incident, the crew was unable to extinguish a hidden in-flight fire that eventually led to a flash fire engulfing the interior of the plane and killing 23 passengers.

One possible means to suppress in-flight fires is the use of a waterspray system which can be automatically or manually activated to extinguish or control a cabin fire. Experimental work indicated that such a system would be effective in controlling cabin fires [7]. This paper also proposed ways to resolve technical issues regarding the installation and operation of such a system. Despite possible limitations, waterspray systems have a number of life safety features such as limiting fire propagation in the cabin, extending the time of survivable conditions in the cabin by cooling the hot gases and by scrubbing water soluble gases from the atmosphere (such as HCl, HF and HCN) and by hardening the fuselage, thus minimizing the threat of external fires gaining entry into the cabin [7]. The appropriate design of such systems is an important issue in ensuring life safety. A recent study dealing with protecting aircraft cabins from external fires also used waterspray systems [8,9]. In this study, an effective system was developed that achieved a 7 min extension of survivable conditions in the cabin using a 3 min discharge of approximately 90 L of water.

This paper presents a study of the use of a Computational Fluid Dynamics (CFD) computer model to assess the effectiveness of a waterspray system for aircraft cabin applications. CFD models are an effective method for investigating fire suppression [10-13]. They enable the visualization of conditions in the vicinity of the fire and, hence, assist in determining the impact of parameters which could affect fire suppression. They also provide a picture of the conditions in the aircraft cabin during the fire, thus enabling a determination of the time when untenable conditions will be reached.

DESCRIPTION OF THE MODEL

The computer model, TASCflow, developed by Advanced Scientific Computing Ltd. [14], was used for the work described in this paper. TASCflow is a general three-dimensional CFD model with capabilities in handling

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laminar and turbulent flows, incompressible and compressible, multi-component fluids, porous media, Lagrangian particle tracking, reacting combusting flows, conjugate heat transfer, surface-to-surface radiation, rotating frames of reference and subsonic, transonic and supersonic flows. The grid generation features of TASCflow include the ability to handle non-orthogonal boundary fitted grids, grid embedding and grid attaching.

To simulate liquid pool fires and their extinguishment using fine watersprays, a number of new sub-models were developed and existing sub-models were modified. These improvements to TASCflow are described in the following sections.

Fuel Evaporation and Combustion

Details of the combustion process were modelled in order to determine the factors affecting fire extinguishment using fine watersprays. Several mechanisms may contribute to the extinguishment of a fire; namely, insufficient oxygen, heat extraction by the water spray, insufficient fuel evaporation or blowing of the flame off the pan. A simplified fuel evaporation and combustion model was developed to assist in understanding the relative importance of each of these suppression mechanisms.

The fuel evaporation rate, $\dot{m}_f$ [$kg/(m^2 s)$], was computed from a balance of the radiant energy reaching the fuel surface, $\varepsilon_r \sigma T_r^4$ [W/m^2], the re-radiating energy $\varepsilon_r \sigma T_f^4$ [W/m^2], and the latent heat of vaporization of the fuel, L_v [J/kg].

$$\dot{m}_f = \frac{2\varepsilon_r \sigma \left(T_r^4 - T_f^4\right)}{\left(2-\varepsilon_r\right) L_v} \tag{1}$$

where T_f is the fluid temperature, T_r is the temperature of the gas above the pan, ε_r is the gas emissivity and σ is the Stefan-Boltzmann constant.

The fuel used for this study was heptane. It was assumed that it reacted according to the empirical 4-step mechanism developed by Hautmann et al [15]. The volumetric rate of each reaction, R_f [$kg/m^3/s$], was controlled by the lesser of the kinetic reaction or turbulent mixing rates. The kinetic reaction rate is given by Hautmann et al [15] in the form:

$$R_f = A_c T^{\beta} C_f^n C_o^m \exp\left[{-E_T}/{T}\right] \tag{2}$$

where A_c is the pre-exponential factor [$kg/m^3/s/K^b/(mol/m^3)^{(m+n)}$], E_T is the activation temperature of the reaction [K], T is the average fluid temperature [K], C_f and C_o are the concentration of fuel and oxidant species in each reaction [mol/m^3], respectively, and b, n and m are constants.

As applied, there is no account made in the kinetic rates for turbulent temperature or concentration fluctuations. This model was tested and compared with data over an equivalence ratio range of 0.12 to 2.0 and a temperature range of 960 to 1540 K by Hautmann et al [15].

The kinetic model limits the combustion rate for temperatures less than 1200 K. At higher temperatures, the reaction rate is assumed to be limited by the turbulent mixing of the reactants which is proportional to ε/k according to the eddy dissipation model of Magnussen [16] given by:

$$R_f = A_t\, \rho \frac{\varepsilon}{k} \min\left[Y_f, \frac{Y_o}{s_f}\right] \tag{3}$$

where, k is the turbulent kinetic energy [m^2/s^2], e is the turbulent dissipation rate [m^2/s^3], Y_f and Y_o are the mass fractions of the fuel and oxidant, respectively, s_f is the mass stoichiometric coefficient of the reaction, and A_t is a constant with a value of 32.

For the present investigation, this combustion model was sufficient to account for the effects of insufficient oxygen, slow fuel evaporation and slow reaction rate on the extinction process. In general, flame extinction would occur when the temperature or available oxygen in any given control volume became so low that the heat generating reaction steps were too slow to maintain the reaction. Extinction was generally observed when the temperature in any given cell decreased below 800 K.

Injection of Water Droplets

Fine watersprays were treated using a Lagrangian tracking model [17,18]. Individual droplets were tracked from their point of injection until they evaporated. The nozzle used for generating the fine waterspray was modelled using a number of point sources. At each point source, droplets were randomly injected in different directions to generate a solid cone spray pattern. To represent the measured droplet size mass distribution of the spray, five separate group of droplets were defined, as shown in Table 1. The mass associated with each group of droplets was related to the experimentally-measured distribution of the droplets from the nozzles [19].

Table 1. Droplet size distribution used in the model.

Droplet diameter (μm)	Percentage
190	13
240	17
290	19
340	35
390	16

To maintain the transient nature of the simulation, droplets were injected at each time step and tracked for the duration of that time step. In the next time step, the existing droplets were tracked and a new set of droplets was injected at the nozzle. This process could result in several hundred thousand droplets in the domain at any given step, however, the total number was found to be self-limiting since the number of droplets which evaporated or were collected on a surface eventually equalled the number injected in any given time step.

DESCRIPTION OF THE PROBLEM

For this study, the same cabin and fire characteristics were used as the one used in Reference [20], in which the interior of a passenger Boeing 737 aircraft was used, as shown in Figure 1. The cabin had a length of 17.1 m, a floor width of 3.3 m and a height of 2.1 m. A 23 × 23 × 77 grid was generated for the cabin, as shown in Figure 2. The cabin fittings consisted of passenger seats arranged in a two- and three-seat configurations with a single aisle and overhead passenger storage bins.

To simulate a 50 kW fire [20], a pan containing heptane fuel with the size of 320 mm × 380 mm × 19.5 mm was used located in the aisle at half the cabin length. An embedded grid with 7 × 16 × 25 control volumes was placed around the pan, as shown in Figure 2, to provide enough grid resolution around the fire pan to capture the recirculating flow around the pan lip. This embedded grid was required to stabilize the fire. The fuel used for the simulations was heptane. The total number of grid points used for the simulations was 43,533.

The aircraft ventilation system was simulated by assuming a uniform venting at the ceiling and floor. The supply vents were located at the top of the ceiling and the return vents were situated at the floor in the left and right corners, simulating a ventilation configuration proposed in Reference [20]. Both the ceiling and floor vents extended along the entire length of the cabin. The vent areas were treated as porous surfaces with a porosity of 0.1. The ventilation rate used was 0.48 kg/s which gives a complete air change every 3 minutes [20]. All the solid walls in the aircraft cabin were treated as adiabatic walls with a thermal emissivity of 0.9. The ambient temperature used was 19°C.

For this study, a single fine waterspray nozzle was mounted near the ceiling directly above the fire pan, which represents optimum nozzle location. The nozzle used in this simulation was a 3/4" water mist nozzle with a spray angle of 150° producing a droplet size distribution as shown in Table 1. This type of nozzle was chosen because it was successfully modelled in Reference [12] with predictions comparing very well with experimental data.

RESULTS AND DISCUSSION

The computer model was used to perform four simulations with mass flow rates of 71, 142, 285 and 570 g/s, as shown in Table 2, to determine the effect of this parameter on extinguishment. The fire development was computed by the model using the combustion submodel. The fire reached a heat release rate of approximately 50 kW in 60 s. The temperature conditions in the cabin at 60 s are shown in Figure 3. This figure shows the isothermal lines along a longitudinal and a cross-sectional plane in the cabin both passing through the pan centre. The figure shows that, at this time, the hot layer in the cabin has a temperature of approximately 60°C, while over the fire plume, the ceiling temperature is approximately 120°C. Figure 4 shows the velocity vectors in the cabin at 60 s.

Application of water started at 60 s by activating a single fine waterspray nozzle located near the ceiling above the pan centreline. All simulations performed used the same nozzle location and characteristics except for the mass flow rate which was varied as shown in Table 2.

Table 2. Simulation cases

Case	No. of nozzles	Mass flow rate (g/s)	Remarks
1	1	71	No Extinguishment
2	1	142	No Extinguishment
3	1	285	Extinguishment
4	1	570	Extinguishment

Figure 5 shows the computed heat release rate for the four cases. At 60 s, the time of nozzle activation, the heat release rate was 50 kW for all cases. Immediately after nozzle activation, the heat release rate decreased rapidly, however only the simulations with a mass flow rate of 285 g/s and 570 g/s resulted in extinguishment. With 285 g/s, the fire was extinguished within 5 s while, with 570 g/s, the fire was extinguished within 1.5 s. In the other two cases, the fires redeveloped after a few seconds to their full intensity and the waterspray system was not able to extinguish them.

Figure 6 shows the water evaporation rate determined for the four tests, which is an indicator of waterspray effectiveness. The figure shows that the initial high evaporation rate for the 285 g/s and 570 g/s cases was reached during the first 2 s of waterspray. This high evaporation rate absorbed large amounts of heat, resulting in quick cooling of the flame, reduced radiation fluxes to the fuel surface and, eventually, fire extinguishment. The simulations with 71 g/s and 142 g/s had considerably lower evaporation rates. These low evaporation rates were not able to cool the flames and suppress these fires.

Another indicator of the effectiveness of the waterspray system is its ability to penetrate the fire plume and reach the fuel surface. The amount of water reaching the fuel surface for all cases is shown in Figure 7. For the simulation with a

water mass flow rate of 570 g/s, the water reaching the pan peaks at approximately 23 g/s while, for the 285 g/s simulation, approximately 10 g/s of water reaches the pan. In the case with 142 g/s, only approximately 4 g/s of water reaches the fuel surface while, in the case with 71 g/s, little or no water reached the pan.

The computed ceiling temperatures above the fire are depicted in Figure 8. At the time of nozzle activation, the ceiling temperature is approximately 120°C. With the activation of the nozzle, the temperature decreases for all cases. In the case of the 570 g/s and 285 g/s water flow rates, the decrease is very rapid reaching 40°C in approximately 5 s after nozzle activation. In the case of 142 g/s, the temperature decreases to approximately 40°C within 10 s of waterspray and remains between 40 and 60°C for the duration of the simulation. In the case of 71 g/s, after the initial drop to approximately 50°C, the temperature fluctuates between 60 and 85°C.

Figure 9 shows temperature contours in the cabin at 30 s after nozzle activation for the case with the 71 g/s water flow rate. Most of the cabin has a temperature below 40°C indicating that, in terms of temperature, and for the assumed fire with fixed area, the waterspray system, even at this low flow rate, can maintain tenable conditions in the cabin for the passengers.

Figure 10 shows the constant temperature surface of 500°C, 25 s after nozzle activation and some waterspray trajectories, as well as the velocity vectors for the airflow in the test facility for the case with 71 g/s water flow rate. The results indicate that the fire plume does not allow the water droplets to reach the seat of the fire, as shown by the droplet trajectories shown in Figure 10a. The inability of the water droplets to reach the fire seat results in no extinguishment, however, the droplets are able to cool the hot gases outside the plume area and maintain low temperatures in the cabin.

Figure 11 shows the results for the case with 285 g/s water flow rate, 2 s after nozzle activation. The droplet trajectories, in this test, reach the fuel pan. The velocity vectors show that the downward flow of air created by the droplets also extend to the fuel pan pushing the fire plume to the side. The cooling of the fire gases by the water droplets and the push of the fire plume to the side of the pan by the air flow results in extinguishment.

SUMMARY

The extinguishment of aircraft cabin fires was modelled using the CFD model TASCflow. The fire was modelled by burning heptane contained in a pan located in the aisle and the waterspray system used was a single fine waterspray nozzle located near the ceiling above the pan. The results of the simulations are promising as they show that this complex problem can be modelled and that the impact of various parameters, such as amount of water needed for fire extinguishment, can be predicted.

The results presented show that, with sufficient water mass flow rate, a waterspray system can extinguish cabin fires quickly. Although lower mass flow rates resulted in no extinguishment, the predicted results indicate that for the assumed fire, with a fixed area, the system was able to control the fire and to maintain the temperature in the cabin at survivable levels.

These results are only an initial attempt at evaluating the use of fine waterspray systems in extinguishing aircraft cabin fires. A systematic study of all parameters involved is necessary for the development of general design guidelines for fine waterspray systems.

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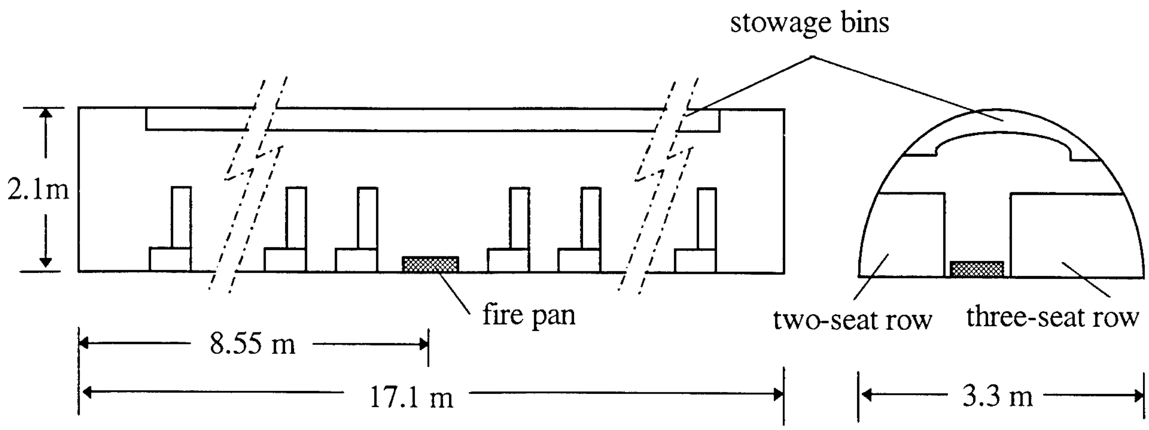


Figure 1. Aircraft cabin geometry used in the model.

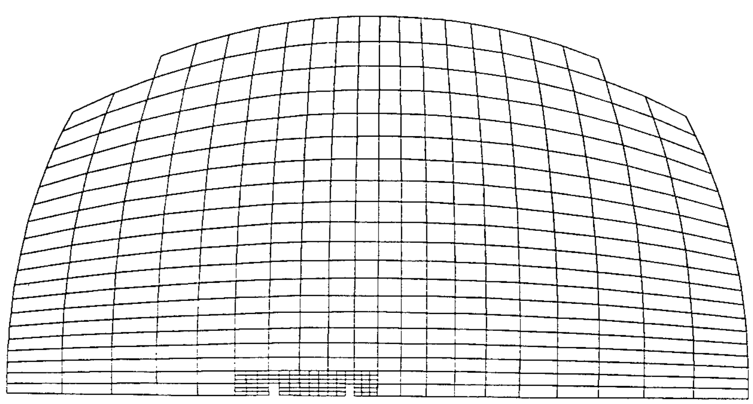


Figure 2. Cross-section of cabin with computational grid showing grid embedding over the fire pan.

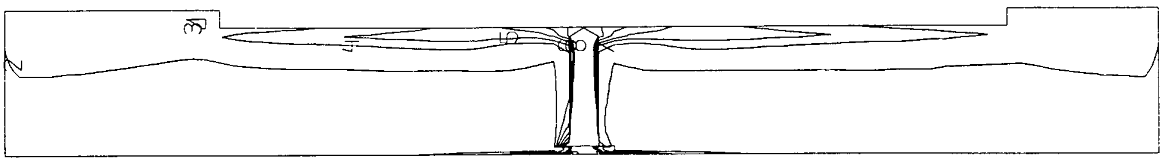


Figure 3a. Isothermal lines on a longitudinal plane over fire pan at 60 s after ignition (contour interval 20 °C with level 1 at 20 °C and level 8 at 160 °C).

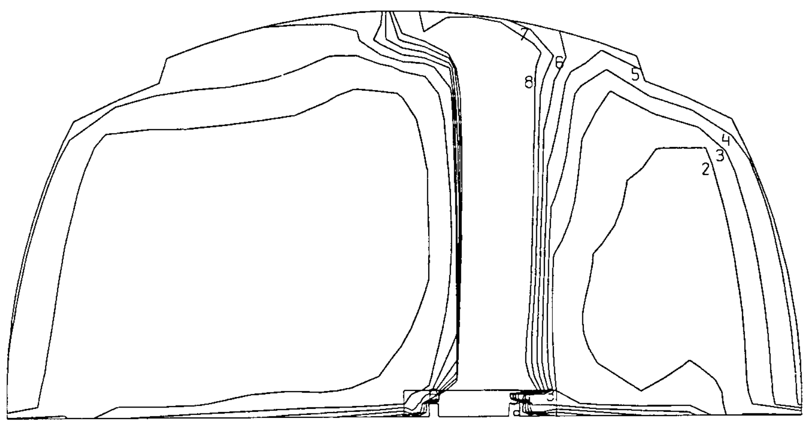


Figure 3b. Isothermal lines on a cross-section over fire pan at 60 s after ignition (contour interval 20 °C with level 1 at 20 °C and level 8 at 160 °C).

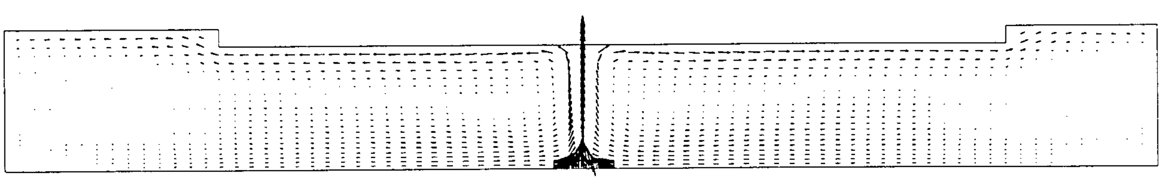


Figure 4. Velocity vectors on a longitudinal plane at 60 s after ignition (maximum velocity 1.1 m/s).

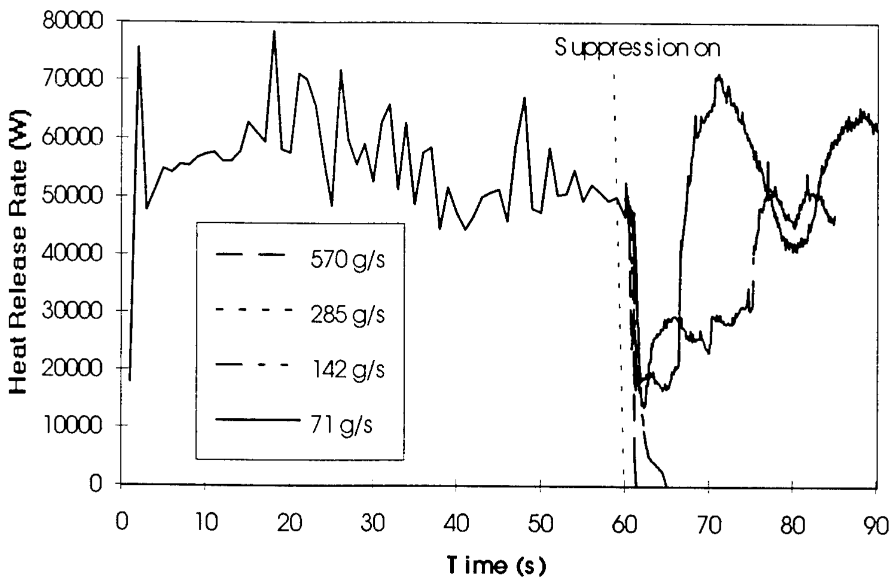


Figure 5. Heat release rate for four cases.

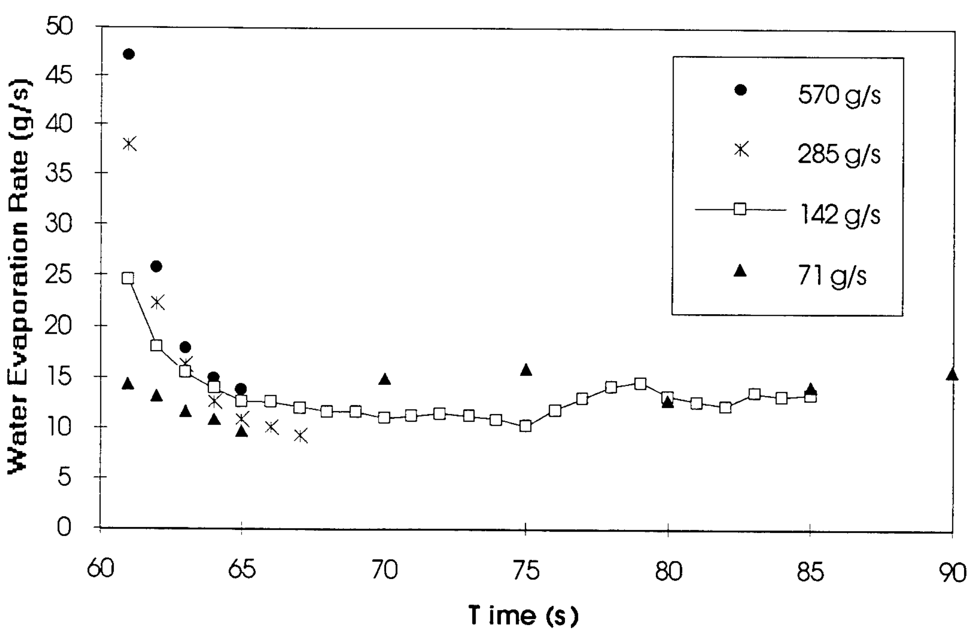


Figure 6. Rate of water evaporated for the four cases.

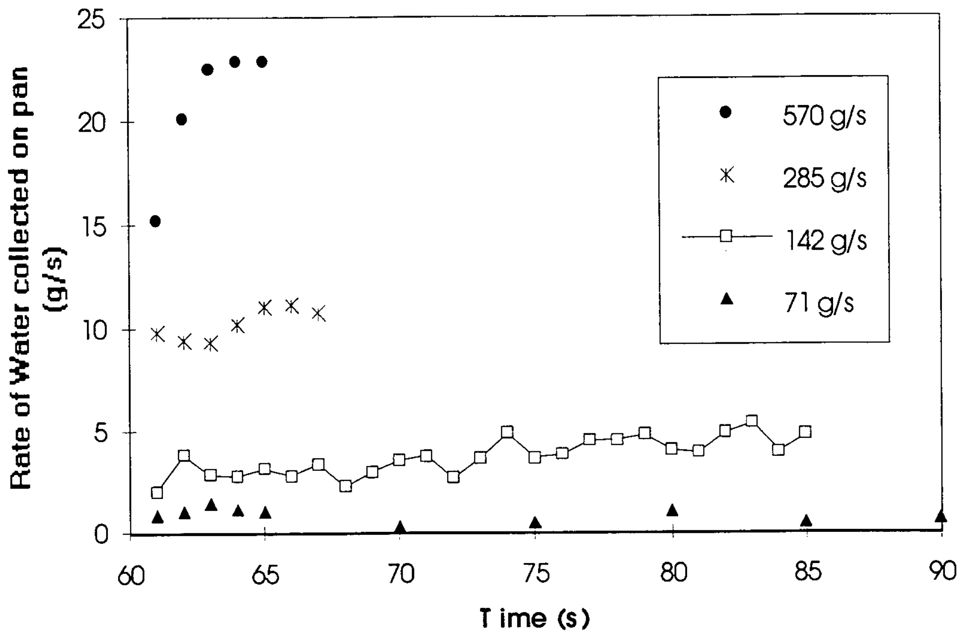


Figure 7. Rate of water accumulated in fire pan for the four cases.

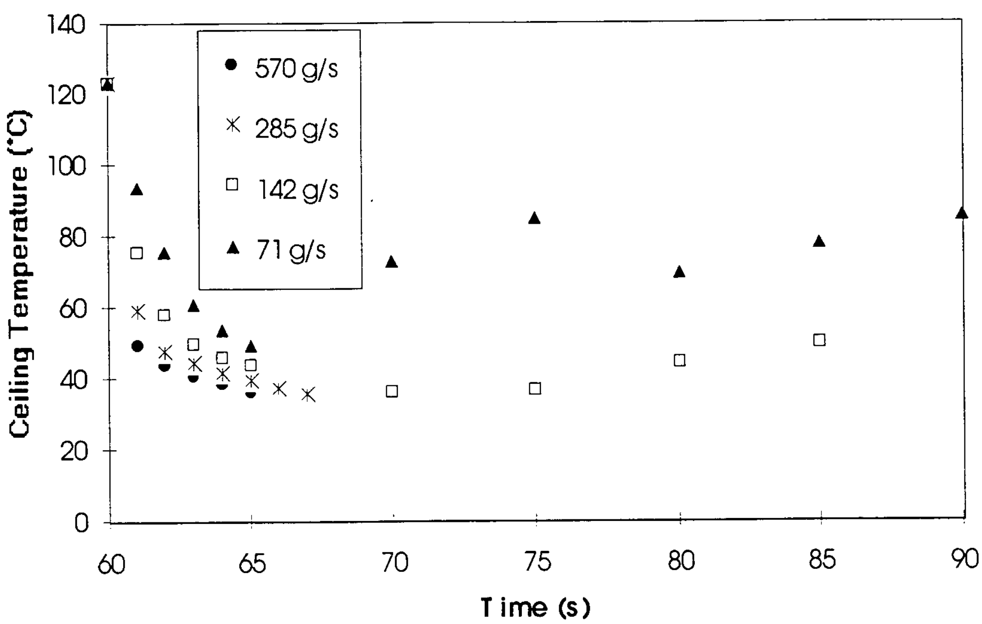


Figure 8. Temperatures above fire pan one grid down from the ceiling of the cabin for the four cases.

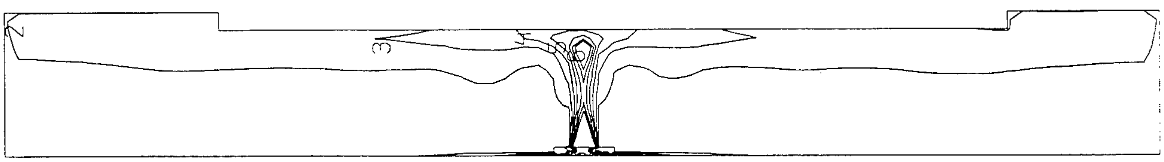


Figure 9a. Temperature contours on a longitudinal plane over fire pan at 30 s after nozzle activation for the 71g/s case (contour interval 20 °C with level 1 at 20 °C and level 8 at 160 °C).

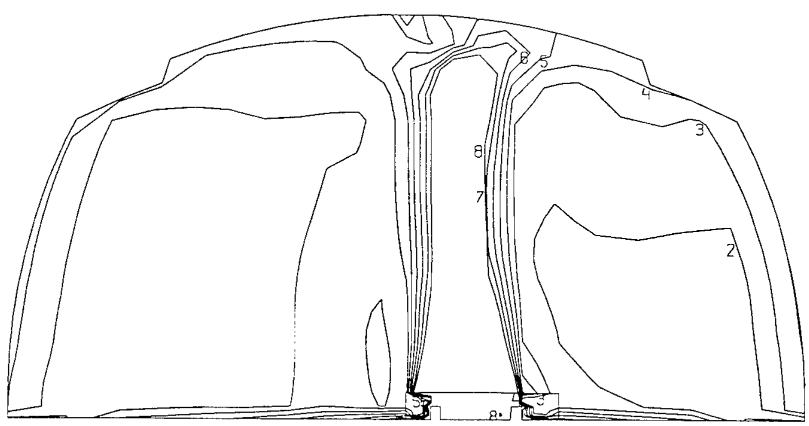
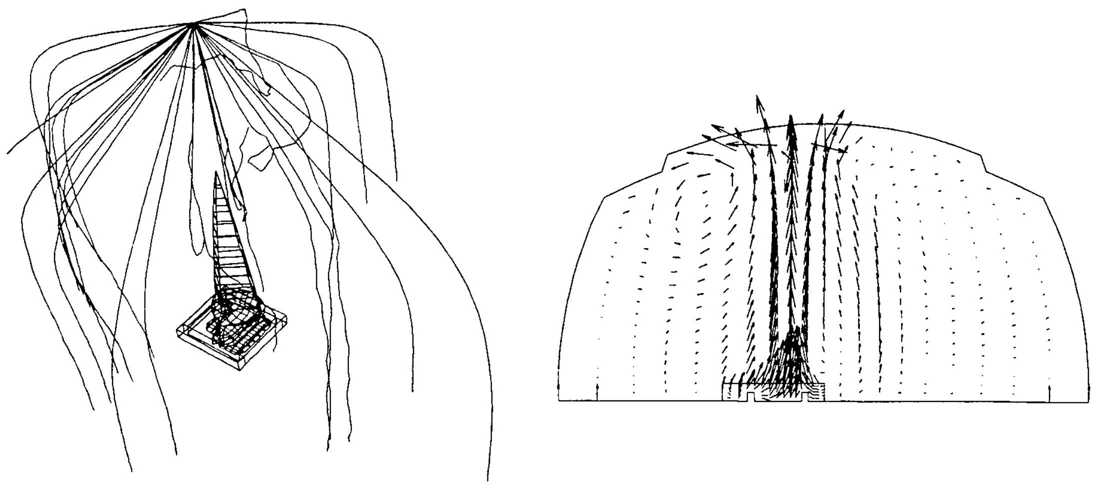
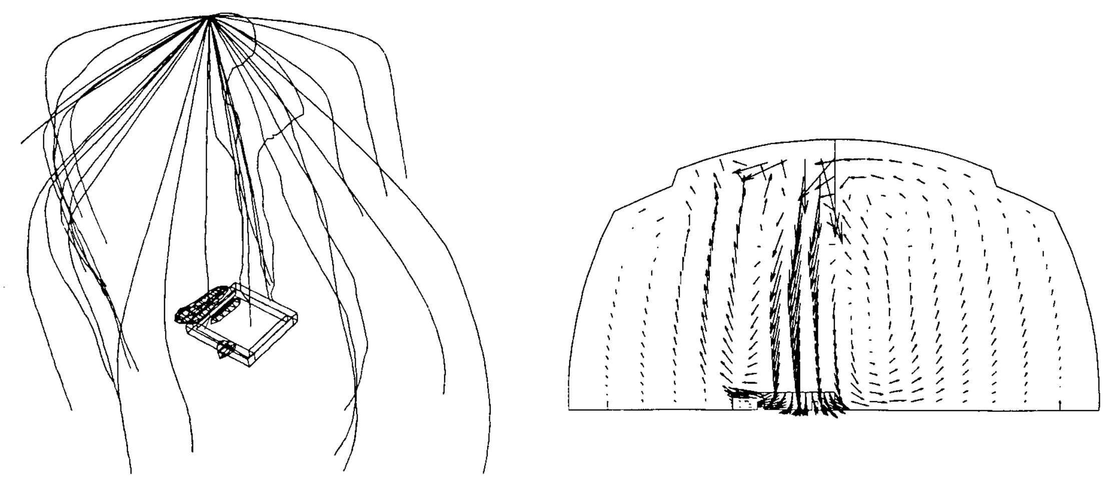


Figure 9b. Temperature contours on a cross-section over fire pan at 30 s after nozzle activation for the 71g/s case (contour interval 20 °C with level 1 at 20 °C and level 8 at 160 °C).



(a) (b)

Figure 10. (a) Water trajectories and constant temperature surface of 500 °C, and (b) velocity vectors (maximum velocity 3.0 m/s), 25 seconds after waterspray activation for the case with 71.0 g/s.



(a) (b)

Figure 11. (a) Water trajectories and constant temperature surface of 500 °C, and (b) velocity vectors (maximum velocity 4:4 m/s), 2 seconds after waterspray activation for the case with 285.0 g/s.

DISCUSSION - PAPER NO. 5

E.R. Galea (Question)

The use of water mist systems on aircraft is intended to either (a) suppress an onboard fire (either in cargo hold or passenger cabin), or (b) make conditions more survivable within the cabin, providing passengers with more time to exit. In the case of suppression, it will generally be solid fuels which are burning - either cabin materials or cargo within the hold. The combustion model presented in the Paper is restricted to liquid fuels. How do you cope with solid fuels, flame spread over solid surfaces and the impact of 'surface wetting'?

G. Hadjisophocleous - Author/Speaker (Response)

The model presented investigated the effectiveness of extinguishing liquid fuel fires using water spays. The importance of this is that for this type of fire, traditionally water is not recommended; however the model, as well as experiments, showed that such systems could be effective. The model does not consider at the moment solid fuels, and the impact of surface wetting, although I believe that the effectiveness at extinguishing such fuels will increase compared to that of extinguishing liquid fuels. Future work is directed at modelling solid fuels.

D. Dierdorf (Question)

There is considerable controversy regarding the effects of droplet size and momentum on the efficiency of extinguishment. Do you intend to use this model to explore these effects?

G. Hadjisophocleous - Author/Speaker (Response)

Yes, the model can consider the effects of droplet size distribution, and droplet momentum. These parameters are needed to define the nozzle used in the model. The effect of droplet size was investigated and presented at the Heat Transfer 96 Conference, July '96, Italy.

J.-M. Buchlin (Question)

Does the modelling take into account the radiative heat transfer between the droplets and the burning gases? If yes, what type of radiative model is implemented in the computer code?

G. Hadjisophocleous - Author/Speaker (Response)

The model has a diffusion radiation model which considers the impact of the droplets on the gas absorption coefficient. Radiation from the gases to the droplets is modeled using an effective heat transfer coefficient.

Heat Transfer Mechanism and "Boil Over" in Burning Oil-Water Systems

Prof. Dr. H.G. Schecker
Fachbereich Chemietechnik
Chem. Verfahrenstechnik
Emil-Figge-Str. 70
44221 Dortmund
Germany

DISCUSSION - PAPER NO. 6

J.-M. Buchlin (Question)

How do you explain the temperature rise of 300°k due to boil over?

M.G. Schecker - Author/Speaker (Response)

We suppose that at the moment of the boil over, the same phenomena will happen as with water steam distillation. We think that, thereby, the evaporation rate of the fuel will be increased. As we have an excess of air in some parts of the flame, that means that the combination and heat production rate will be increased.

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

USING MATHEMATICAL MODELS TO PREDICT THE DEVELOPMENT OF AIRCRAFT CABIN FIRES.

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Wellington Street
London SE18 6PF, U.K.

1. SUMMARY

Computer based mathematical models describing aircraft fire have a role to play in the design and development of safer aircraft, in the implementation of safer and more rigorous certification criteria and in post mortuum accident investigation. As the cost involved in performing large-scale fire experiments for the next generation 'Ultra High Capacity Aircraft' (UHCA) are expected to be prohibitively high, the development and use of these modelling tools may become essential if these aircraft are to prove a safe and viable reality. By describing the present capabilities and limitations of aircraft fire models, this paper will examine the future development of these models in the areas of large scale applications through parallel computing, combustion modelling and extinguishment modelling.

2. INTRODUCTION

The mathematical simulation of fire has a wide, and as yet largely untapped, scope of application within the aviation industry. The function of mathematical models is to provide insight into complex behaviour by enabling designers, legislators and accident investigators, to ask 'what if' questions.

Fire models could be used to determine the impact of the spread of fire hazards such as smoke, heat and toxic gases resulting from an accident and hence predict the development of life threatening conditions within the cabin. Fire models also have application in the development of fire protection and fighting strategies such as the development of water mist systems for aircraft. Validated fire models have the potential to be used by:

Aircraft Designers, to assess the impact of new aircraft cabin layouts on the spread of fire hazards such as smoke under various fire scenarios. Fire models could be employed as design aids for the next generation UHCA, bringing fire considerations into the early stages of aircraft design,

Accident Investigators to determine the impact of the spread of fire hazards such as smoke, heat and toxic gases resulting from an accident and hence predict the development of life threatening conditions within the cabin; and finally,

Legislators, to assess the suitability of new designs and fire protection and fighting devices such as water misting systems.

3. FIRE FIELD MODELS, WHAT ARE THEY?

Fire field modelling [1] has been a reality for twenty years, however its recent success in uncovering details of the fire mechanism responsible for the Kings Cross tragedy [2] highlight its value as a fire analysis tool.

At the heart of the fire field simulation problem lies one of the most difficult areas in Computational Fluid Dynamics (CFD): the numerical solution of recirculating, three-dimensional turbulent buoyant fluid flow with heat and mass transfer. Field models differ from their simpler zone model [1] counterparts in that they employ CFD software that can describe and predict the flow of hot turbulent fire gases across a whole field of points in the enclosed compartment.

The equations which describe a field model consist, in general, of a set of three dimensional, time dependent, non-linear partial differential equations: the Navier-Stokes equations. These are essentially the same set of equations that aircraft designers use to design aerodynamic shapes such as wings. Fire field models employ CFD software to solve the fundamental equations of motion and conservation for the fire at discrete points in time and space. To facilitate this, the volume of the fire compartment is divided into thousands of small volumes or computational cells. The appropriate number is dependent upon the type of fire enclosure, the order of accuracy required and, ultimately, the speed of the computer and the size of its memory. A small room may require around 5000 cells, while the interior of a small passenger aircraft requires in excess of 50,000.

The equations describing the fire system are solved simultaneously in each cell to obtain the various parameters of interest such as temperature, pressure, gas velocities, smoke concentration etc. Thus, the model can display quantitative differences in the physical parameters throughout the computational grid. Using a three-dimensional framework of Body Fitted Co-ordinates (BFC), it is possible to construct realistically shaped fire enclosures. These could be as different as a spacious populated enclosure such as an aircraft cabin [3,4] or the confined environment of a cable duct.

4. THE APPLICATION OF FIRE FIELD MODELS TO AIRCRAFT FIRE SCENARIOS.

Since 1985 the Fire Safety Engineering Group (FSEG) of the University of Greenwich (UOG) has been developing aircraft cabin fire field models [3-8]. Over the years this work has been supported by various groups, including the U.K. Civil Aviation Authority (CAA), the U.K. Engineering and Physical Sciences Research Council (EPSRC) and British Aerospace Plc.

Field models with a flow domain describing the internal passenger space and the surrounding external region of the fuselage could be used to determine aircraft venting performance, both natural and forced. This would be useful for evaluating the impact of the spread of fire hazards such as smoke, heat and toxic gases resulting from either an in-flight or post-crash fire. The technique can also be used as a tool to aid in the design of cabin

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

ventilation systems in order to determine optimal levels of ventilation performance for maximum passenger comfort.

External post-crash fuel fires could be examined and their interaction with the prevailing environmental conditions and fuselage orientation determined. Once the external fire has gained access to the internal regions of the aircraft, either through, an existing rupture, open doorway or 'burn-through', field models can be used to determine the development of the hazardous cabin fire environment.

One of the earliest aircraft cabin fire calculations produced by the FSEG compared model predictions with measured data derived from a series of experiments produced by the Johnson Space Centre [9]. These experiments were conducted in an empty B737 fuselage, with a fire source consisting of a fuel pan containing 4.5 l of Jet A-1 fuel located on the cabin floor just off the cabin centre. The B-737 had the forward and aft sections removed and replaced with bulkheads containing doors.

This simple geometry was modelled accurately in three-dimensions using a BFC grid consisting of 20,328 computational cells and the fire was represented by a simple constant heat source [3] representing a non-spreading fire. The results demonstrated that such a model was capable of predicting the observed trends in temperature distribution throughout the aircraft.

Using the B-737 geometry and the previous fire specification, several other hypothetical fire scenarios were simulated representing various 'what if' cases. These consisted of investigating the effect of various fuselage openings [8] and cabin partitioning [3] on the temperature distribution within an empty burning cabin. Another series of fire simulations involved the B-737 fuselage fitted with seats and overhead stowage bins and considered the effect of the cabin ventilation system on the developing fire atmosphere [3,8].

The cabin openings consisted of combinations of external doors and ceiling apertures. The ceiling aperture was intended to simulate a rupture in the fuselage. Four cases were examined, these consisted of Case A: aft left door open, Case B: forward and aft left doors open, Case C: left and right aft doors open and Case D: left aft door and the ceiling above the door are open.

The model results clearly showed that the temperature distribution within the fuselage was strongly affected by the nature of the fuselage openings. The highest temperatures were found in Case A (single side opening). This was consistently true, throughout the length of the fuselage and in the vicinity of both the floor and ceiling. In this case temperatures near the floor were typically 80°C while temperatures in the ceiling region were about 115°C.

Of the four cases examined, Case D (ceiling and side opening) generated minimum temperatures in the ceiling region. In the aft section of the cabin temperatures were typically 80°C while in the forward section temperatures were in the vicinity of 95°C. In this case, the model predicted that relatively cool air was entrained into the cabin throughout the open area of the left door while hot ceiling gases were vented out through the ceiling opening. In the lower regions of the cabin, Case B (forward and aft left doors), generated the lowest temperatures. In this scenario, temperatures near the floor were typically 60°C.

These simulations suggest that fuselage openings have a profound affect on the developing cabin atmosphere and hence on the threat to human life. Simulations of this type may be useful in suggesting fire fighting strategies and in investigating aircraft accidents involving fire [8].

The effects of cabin compartmentation on the temperature distribution throughout the cabin were also investigated [3]. The cabin partition consisted of a bulkhead containing an open doorway. The bulkhead was located in the forward section of the cabin 1.5m from the fire source. This effectively partitions the cabin into two sections, the forward section containing the fire and the aft section.

Model results suggested that the cabin partition offered some degree of protection to the aft section of the cabin. With the bulkhead present, temperatures in the aft section of the cabin were on average 15% lower than the corresponding temperatures in situations without the cabin partition. Conversely, temperatures on the fire side of the cabin are somewhat higher in the partitioned cabin compared with temperatures in the unpartitioned cabin.

A detailed investigation of the model predictions revealed that the ceiling soffit intercepts the hot ceiling jet. Some of the hot gases are diverted under the soffit, while immediately behind on the fire side of the cabin, a small region of recirculating air develops. These results suggest that cabin compartmentation may offer passengers some protection from elevated temperatures in the event of fire. There is some experimental evidence [10] to support these claims.

With the B-737 cabin fitted with seats, ceiling panels and overhead stowage bins the effect of the aircraft's air-conditioning system on the temperature distribution within the burning fuselage was examined [3,8]. Three venting scenarios were investigated. The first case, case A, involved no forced ventilation. In the second case, case B, fresh air is injected from the ceiling vents while hot air is sucked out from the floor vents. Case B is intended to simulate the operation of the environmental control systems found in most commercial aircraft. In the final case, Case C, the venting in case B was reversed so that air was injected at the floor vents and exhausted through the ceiling vents.

The usefulness of reverse venting in reducing temperatures and smoke concentrations near the floor in building fire scenarios is well known and has been observed in full-scale experimental room fires [11]. The purpose of these simulations was to investigate if similar benefits could be expected in aircraft fire applications.

The results suggested that a reverse flow venting situation greatly reduces the temperature throughout the fuselage in the vicinity of the floor and ceiling. The use of this venting strategy could lead to the control of the rate of spread of fire and smoke within the cabin and hence prolong habitable conditions within the cabin. Such control is particularly relevant to the in-flight fire scenario. These model predictions have subsequently been reinforced by a series of FAA sponsored experiments [12].

5. CURRENT RESEARCH IN FIRE MODELLING

The primary application of current fire field modelling technology concerns the prediction of smoke and heat movement within fire enclosures. While the capabilities of

current fire field models are considerable much research is required to widen their scope of application. Here we will examine the future development of these models in the areas of large scale applications through parallel computing, combustion modelling and extinguishment modelling.

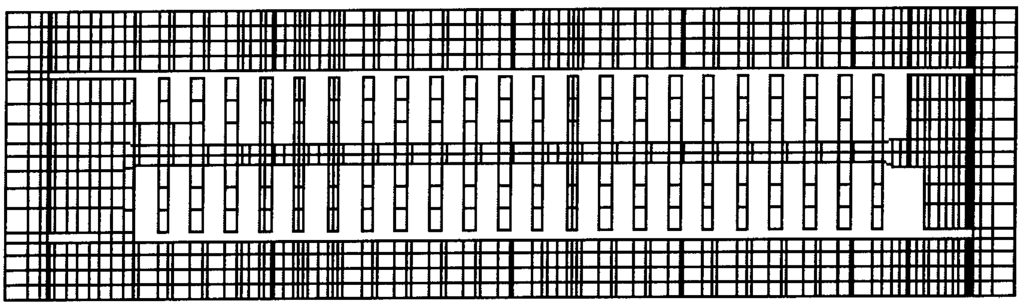
5.1 Parallel Computing.
Field modelling requires an enormous number of calculations to be performed, thereby necessitating the need for considerable computer power. Hundreds of hours of computer time may be required to perform even the simplest of aircraft fire simulations using current generation workstations. The high computational cost associated with fire field models is being tackled through advances in parallel computing hardware and software thereby making these models more affordable and practical. The FSEG have adopted this approach and developed a parallel fire field model [4,13].

The ability of fire field models to exploit parallel computing techniques will enable these models to be accurately and efficiently employed in large geometries such as B777 and A340 aircraft and their successors. Without this capability, compromises in mesh density and model complexity would be necessary in order to make simulations practical.

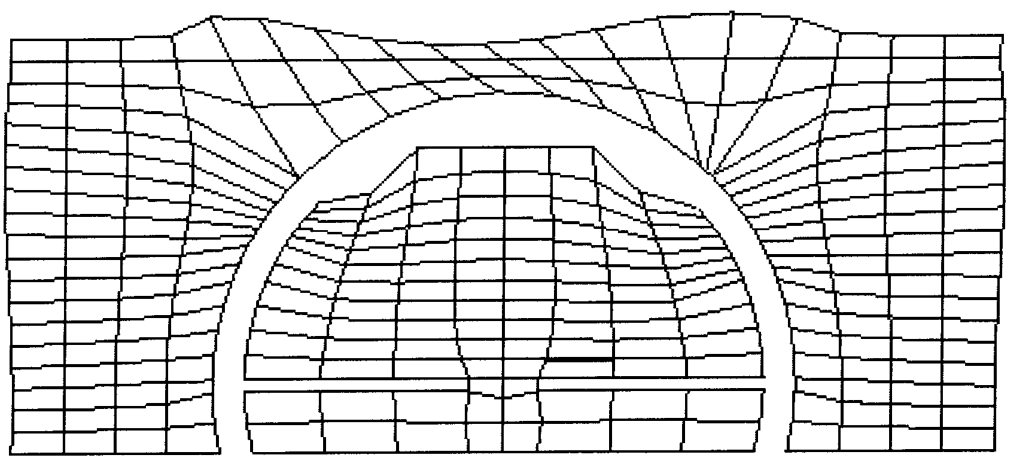
To demonstrate the capabilities of this system the parallel fire model has been used in two aircraft applications. The first concerns a fire scenario involving a reconstruction of the Manchester B737 aircraft fire and the second concerns a hyperthetical UHCA.

5.1.1 B737 Fire.
The first example is intended to simulate a fire similar to that which destroyed the B737 at Manchester Airport on the 22 August 1985. These simulations are fully three dimensional and transient, including a detailed description of the B737 geometry. While the aircraft was preparing for take-off at Manchester airport, an external fuel fire started and eventually gained access to the cabin interior [14]. This disaster (which claimed the lives of 55 people) posed several questions concerning the spread and behaviour of fire gases within aircraft cabins. Through the application of fire models we hope to gain insight into how fatal conditions develop within the aircraft.

As sufficient fire details are not available to accurately define the Manchester fire scenario, this simulation is not intended to reproduce the actual disaster. The simulation may be considered "Manchester like" in so far as the aircraft geometry, door opening sequence, external wind conditions



(A) HORIZONTAL VIEW



(B) CROSS-SECTIONAL VIEW.

FIGURE 1: Computational Mesh in the Boeing 737 fire simulation. Depicted are the (a) plan view and (b) cylindrical section view

(7 knots approaching from 250°) and initial fire location are similar to the reported situation.

The B737 is a single aisle aircraft that is approximately 20.3 m in length with a maximum width and height of 3.216 m and 2.105 m respectively. It has four floor level doors, two front (L1 and R1) and two aft (L2 and R2) along with two additional over-wing (ROW and LOW) exits. Of the six exits available, four were opened and only three were used by escaping passengers. The reported opening times were, R1 70 seconds, L1 25 seconds, ROW 45 seconds, R2 0 seconds. All times refer to time after aircraft came to a stop.

Analysis of the wreckage suggests that the fire initially penetrated the outer skin of the aircraft on the left side in the vicinity of seat rows 17 to 19, below the level of the cabin floor. Having breached the outer skin the fire would have quickly gained access to the cabin.

A body-fitted co-ordinate system was used to fit the computational grid to the actual specifications of the fuselage, whereby the seats, galleys and overhead lockers were all included. A relatively coarse grid of 18x20x104 (37,440) cells was used to describe the aircraft including an extended domain outside the fuselage (see figure 1). During the transient simulation the exits were opened as reported.

There is uncertainty concerning the precise location and spread of the internal fire and its heat release rate. For the simulations presented here the fire was simulated as a volumetric heat source with a time varying heat release rate and fire area. The INTERNAL fire grows to a maximum heat release rate of 720 kW in the first 30 seconds and is initially located under seat rows 17 to 19 on the left hand side. For the first 25 seconds the fire area was 1.0 m^2 growing to 3.39 m^2 after 30 seconds

In order to investigate the impact of the external cross-wind on the internal fire environment two different scenarios were simulated; the first without and the second with a cross-wind. The simulations were performed using a parallel computer consisting of four i860 processors, resulting in the case without wind requiring 97 hours of CPU time to complete 60 seconds of simulation. The nature of the flow generated by these models is highly transient and complex. Computer generated video animation is used to aid in the interpretation of the results. This animation can be viewed over internet the [15].

For the first 25 seconds, whilst the forward exit was closed, the cross-wind did not have a significant effect on the internal flow and temperature conditions. After this time the L1 exit, which was facing the oncoming wind, was opened. This allowed the wind to enter and hence influence the interior flow and temperature conditions.

After 30 seconds, the results indicate that the wind generated internal flow opposes the flow of the hot combustion gases forward of the fire. However, aft of the fire the two flows are in similar directions creating a more prominent outward flow through the open aft exit (see figure 2) . As a result of this flow, temperatures are reduced in the front part of the cabin and increased in the aft part of the cabin (see figure 3).

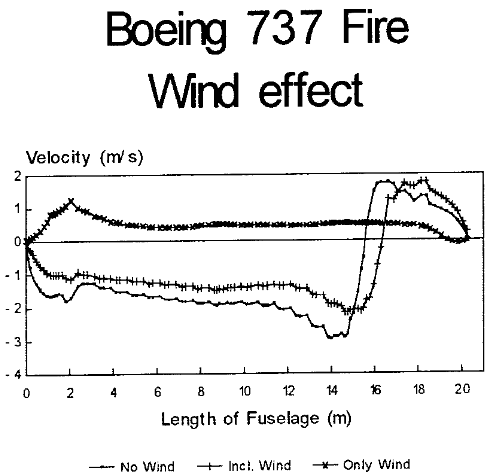


FIGURE 2: Velocity distribution along the centre of the aircraft from forward to aft 1.9m above the floor.

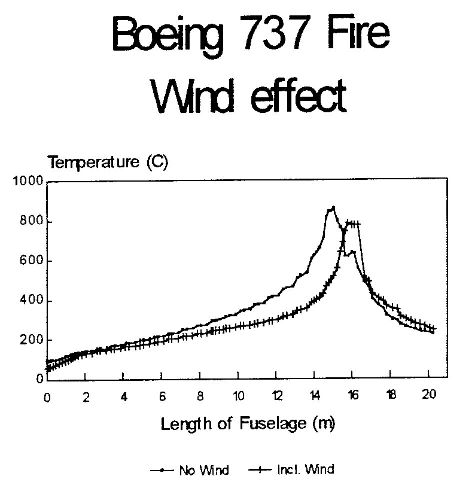


FIGURE 3: Temperature distribution along the centre of the aircraft from forward to aft 1.9m above the floor.

The peak temperature measured in the aisle is also reduced in the presence of wind. Note that at ceiling height, temperatures are in excess of 800°C in a small localised region where the plume impacts the ceiling. Pure aluminium has a melting temperature of approximately 650°C and experiments conducted for the CAA [16] suggest that a 1mm thick aluminium sheet placed in a furnace at 950°C will burn through after 80 seconds. Burnthough by the interior fire can therefore be expected at some time after 30 seconds.

A well-defined temperature stratification is also observed within the cabin. While temperatures are high at head height near to the floor they are quite small. Temperature stratifications of this type have also been observed in full-scale aircraft cabin fire experiments [17,18].

The temperature stratification has a major impact on survivable conditions within the cabin. According to the Fractional Effective Dose (FED) model developed by the FAA [19], dry air temperatures of 240°C can be withstood by

clothed individuals for one minute before incapacitation occurs. This figure simply relates to the temperature component of the fire atmosphere and does not take into consideration toxic gases or smoke. From figure 3 it is clear that in the case of fire without wind, this critical temperature is exceeded at head height from seat row 7 back. However, in the case involving fire and wind, the critical temperature is not exceeded until seat row 10 is reached. Close to the floor the situation is much improved. At a height of 0.5 m above the floor, the maximum aisle temperature is less than 140°C. According to the FED model, occupants can withstand this temperature for 6 minutes.

The above scenario represents the first 30 seconds of a 'Manchester type' fire situation. It is intended to continue these simulations to the point where the R1 and overwing exits are opened. It is hoped by investigating the flow that develops under these conditions we will better understand the complex interaction between aircraft, fire and wind. Further details may be found in reference 4.

5.1.2 UHCA Application

UHCA have been proposed which consist of two decks stretching along the entire length of the aircraft. In such aircraft multiple staircases linking the decks may be necessary. Aircraft designs of this magnitude arguably have more in common with hotels than aircraft. Fire models offer aircraft engineers a possible means of exploring the ramifications of fire in these unusual structures and in assessing the likely impact these fires may have on evacuation. For instance, the role of staircases in propagating smoke, heat and fire gases to regions otherwise clear of fire could be examined using fire models. The ramifications of burnthrough to other decks, cabin compartmentation and forced ventilation strategies on the associated spread of fire hazards could also be examined. Possibly of greater importance, means of preventing the spread of fire hazards may be explored using these models.

To demonstrate the application of fire models to UHCA, FSEG have performed a simulation of a fire on board a hypothetical UHCA. The portion of the aircraft simulated measured 28m in length and consisted of two decks and 260 seats arranged in a twin aisle configuration. The aircraft section contained 3 staircases with 3 pairs of doors on each deck. The fire was located on the lower deck in the vicinity of the central stair, and the doors were open during the simulation (see figure 4). Note the spread of the fire hazards to the upper deck in figure 4. The model consisted of 100,000 cells and required 14 hours of computer time on an 8 processor parallel computer.

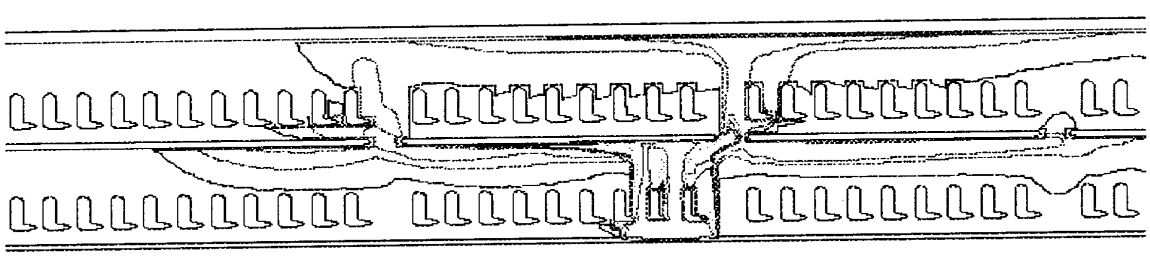


FIGURE 4: UHCA with fire on lower deck. Temperature contours predicted using FSEG fire model.

5.2 Combustion Modelling.

The combustion process is extremely complex. The change from reactants to final products includes many intermediate reactions involving the formation and interactions of numerous short lived species and free radicals. In most instances, these intermediate products and their rates of creation and destruction, are not known. Turbulence further complicates the situation by influencing the mixing of reactants and products. Consequently, in most fire models combustion is assumed to follow a global, one-step chemical reaction mechanism [20], in which fuel reacts with oxidant to give product. The rate of reaction is controlled solely by the turbulent mixing of fuel and oxidant which is determined from calculated flow properties. This approach, while only approximating the combustion process, does give satisfactory results for relatively simple gaseous fuels.

The prediction of flame spread over complex solid surfaces such as aircraft seats, cabin walls and floor linings is currently beyond the scope of field modelling technology and is receiving considerable interest from research groups throughout the world.

As a first approach to this problem, the FSEG is developing a simple solid fuel combustion model to be incorporated within a fire field model. The model is intended for use in engineering applications of fire field modelling and represents an extension of this technique to situations involving the combustion of solid cellulosic fuels. The model consists of a thermal pyrolysis model, a radiation model and an eddy-dissipation model for gaseous combustion. Within the model the flame spread is governed by a set of partial differential equations which express gas phase behaviour, solid phase behaviour and their interaction.

During pyrolysis, solid fuel may undergo melting, shrinking/expanding and charring. The thermal properties of the material will also vary with temperature. Several models have been developed to represent this complicated process [21,22,23]. The most complex of these models makes use of kinetic rate laws [22,23] and a large number of material properties [21]. Compared with these more sophisticated models, the thermal pyrolysis model [21] uses the relatively

simple concept of the pyrolysis temperature as a first approximation. The relative simplicity of this model makes it an attractive proposition for engineering applications. This simple pyrolysis approach has been adopted here. The pyrolysis mechanism is simply described as a process in which combustible gases are given off the surface of the solid fuel at the pyrolysis temperature. While the concept of the pyrolysis temperature is questionable and scenario specific, both physical experiments [24] and theoretical analysis [25] have demonstrated that it provides a fair approximation to the pyrolysis process for various materials. In this model, combustible gases are released from the surface of the solid fuel when it is heated to its pyrolysis temperature T_p. In fires, the energy to sustain this endothermic gasification process is generally supplied by the thermal radiation emitted from the fire and hot combustion products. In addition to radiation, flame spread over the solid fuel is influenced by conduction within the fuel and so this mechanism is included within the model. Conduction allows virgin fuel not directly exposed to radiation to be preheated.

The solid fuel combustion model has been demonstrated through two-dimensional simulations of flaming combustion in a room fire scenario involving a plywood ceiling.The target fuel lining the ceiling is discretised into a number of layers running parallel to the floor. Once a layer of the solid fuel is heated to the pyrolysis temperature T_p, it begins to be gasified while its temperature remains fixed at T_p. As it is being gasified, the solid fuel is consumed one layer at time. Once the lining materials have been gasified, the gaseous combustion model (eddy dissipation model) is activated to simulate the flame spread process. The radiative heat flux from the fire and hot gases and reradiated heat losses from the solid surface are calculated using the radiation model where the scattering coefficient assumes the value $0.01 m^{-1}$ [26].

The first case considers an open room scenario in which a flashover type phenomenon is predicted to occur. The second case considers a sealed room fire scenario in which the closed door is opened after some time. In this simulation a backdraft type phenomenon is predicted to occur.

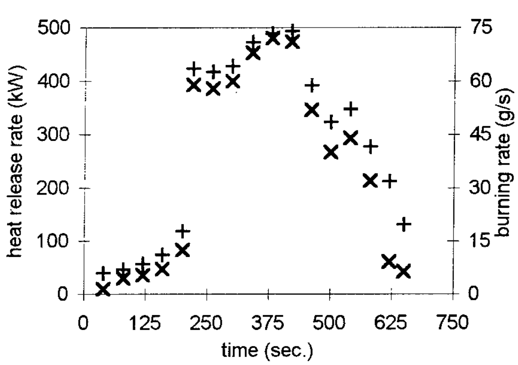


FIGURE 5: Heat release rate of gaseous combustion and burning rate of solid material in case 1. +: the heat release rate of gaseous combustion (kW); x: the burning rate of solid material (g/s).

5.2.1 Flashover

The fire development within the compartment appears to undergo a three stage development. This can most clearly be seen in figure 1 which depicts the heat release rate due to gaseous combustion and the burning rate of solid fuel within the compartment.

The curves are clearly divided into three regions representing three phases of fire development. In the first phase, which lasts for the first 200 seconds, the heat release rate of gaseous combustion in the compartment increases at a slow and fairly constant rate (see figure 6).

At about 220 seconds (see figure 5) a critical point is reached where the fire rapidly passes into the second phase of fire development and the heat release rate of gaseous combustion in the compartment undergoes a sharp increase. This rapid increase is a result of the entire combustible ceiling becoming involved in the fire.

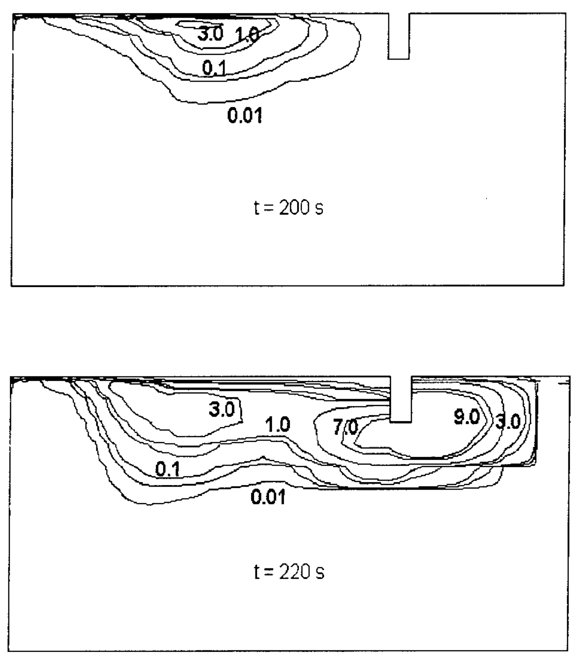


FIGURE 6: Contours of heat release rate of gaseous combustion for case 1 preflashover (t = 200s) and during flashover (t = 220s). Unit: kW.

As a result, the flame erupts out of the compartment (see figure 6), a phenomena often observed in experiments in which flashover occurs. During flashover, combustion within the gaseous phase is more pronounced and involves a greater proportion of the compartment than is observed during the preflashover stage. Over the next period of about 200 seconds the heat release rate of gaseous combustion and the burning rate reach a maximum and maintain a reasonably stable state. The fire is fully developed in this period. During this phase the gas temperature beneath the ceiling reaches a peak of about 1100K. The third phase of fire development occurs approximately after 460 seconds, where the heat release rate begins to rapidly decrease (see figure 5). During this phase all of the remaining solid fuel is consumed.

5.2.2 Backdraft

When the door to the fire compartment is closed, the initial increase in room temperature and ceiling fire spread are more

rapid than those noted in the previous case. As the door is closed, there is no source of fresh air - and hence oxygen - to replenish the oxygen consumed by the combustion. In this case, while the pyrolysis process continues, combustion is incomplete and more and more unburned fuel gases accumulate within the room (see figure 7).

Compared with the previous case, instead of a sharp increase in heat release rate as the fire spreads, the heat release rate increases slowly, however there is a rapid increase in the amount of fuel accumulating within the compartment (see figure 7). After approximately 45 seconds, the heat release rate due to flaming combustion begins to decrease due to the reduction in oxygen concentration. Figure 7 suggests that even as the fire dies down, the amount of fuel accumulating in the compartment continues to increase. This suggests that the pyrolysis process continues as the hot gas mixture provides sufficient energy for the endothermic process to continue.

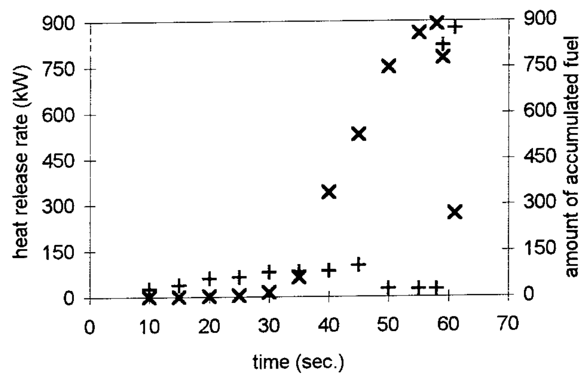


Figure 7: Heat release rate of gaseous combustion and fuel accumulation within the compartment for case 2. +: heat release rate of gaseous combustion (kW); ×: amount of fuel accumulating within the compartment (g).

After 59 seconds, the door of the compartment is opened suddenly. Oxygen rich air is entrained into the room through the lower reaches of the door while the hot fuel rich gas mixture flows out the room through the upper reaches of the door, under the soffit. Almost immediately, this motion of hot fuel rich gases and cool oxygen rich air reignites the combustion process. Initially (i.e. one second after the door is opened), gaseous combustion primarily takes place in the upper layer outside the room, in the doorway and in the lower layer just inside the room. This is due to the nature of the mixing process between the hot fuel rich gases leaving the room and the fresh oxygen rich air entering the room. As a great amount of fuel has accumulated within the compartment (see figure 7), the gaseous combustion is tremendously intense. Furthermore, considerable amounts of combustible gases spill out from the top region of the doorway in a very short space of time generating a large combustion region outside the compartment i.e. the flame is seen to protrude from the compartment

As oxygen rich air mixes with the fuel rich combustion products within the room, flaming combustion erupts through a greater proportion of the compartment in a matter of seconds. These processes result in the marked rapid drop in combustion gases noted in figure 7. This type of behaviour is similar in nature to the hazardous phenomenon known as backdraft. Further details of this work may be found in reference 26.

5.3 Extinguishment Modelling

Another area of interest is the modelling of fire suppressant systems. Such scenarios have obvious application to the development of aircraft water mist systems for use either in cabins or as a replacement for existing halon based systems in cargo holds [27,28]. Using the field modelling approach it is possible to simulate the action of water sprays in a fire compartment.

In this case there are now two interacting physical phases, the gas phase involving the general fluid circulation of the hot combustion products and the liquid phase, representing the evaporating water droplets. The numerical procedure of the fire model must be adjusted to take into account these interacting phases. This set of equations now includes the interphase processes of drag, heat and mass transfer between the liquid and gaseous phases.

One approach to the simulation of these interacting phases is the Euler-Lagrange methodology [29]. In this approach the gas phase is modelled using standard CFD techniques while the discrete phase (water droplets) are modelled using a Lagrangian particle tracking scheme. The motion and properties of individual droplets or packets of droplets are tracked either until they evaporate or come into contact with a surface. Finally, the two phases are coupled using the PSI-Cell method. In this method the particles mass, enthalpy etc are noted as it enters and leaves each cell in the computational domain. Any changes in the values of these quantities are due to gas/droplet exchange and are calculated and added to the appropriate cell in the gas phase as sources. In this manner the temperature and gas flow will effect the trajectory and evaporation rate of the water particles and the particles will react back onto the temperature and velocity field of the gases.

FSEG have developed a water spray model for use in aircraft fire applications. To demonstrate this model a conventional sprinkler system located in a long corridor was simulated. The corridor was 12m in length, 3m in height and 3m in depth. It was meshed using a uniform Cartesian mesh of 100 cells in the horizontal direction, 15 cells in the vertical direction and 15 cells in depth. A fire was arbitrarily situated in the centre of the corridor. The interaction was modelled for 120 seconds in 1 second time steps. The spray was located 5m to the right of the fire, 1m from the end of the corridor. It had a spread of 90° pointing symmetrically downwards, a flow rate of $2.4ls^{-1}$, 1000μm diameter droplets, an initial velocity of $5ms^{-1}$ and a temperature of 20°C. It was modelled using 48 trajectories in 4 rings of 12, equally spaced by angle in both the horizontal and vertical planes. Using a SUN supersparc 10, 40 MHz server, the 120 second simulation required approximately 22 hours of CPU time.

The results of the simulation have been animated and are available for study over the internet [15]. Prior to sprinkler activation, a plume of hot fire gases rises from the fire source and spreads out under the ceiling in a symmetrical manner. Prior to sprinkler activation a symmetrical flow is established and a hot ceiling layer forms which gradually deepens with time. After 10 seconds the sprinkler is activated.

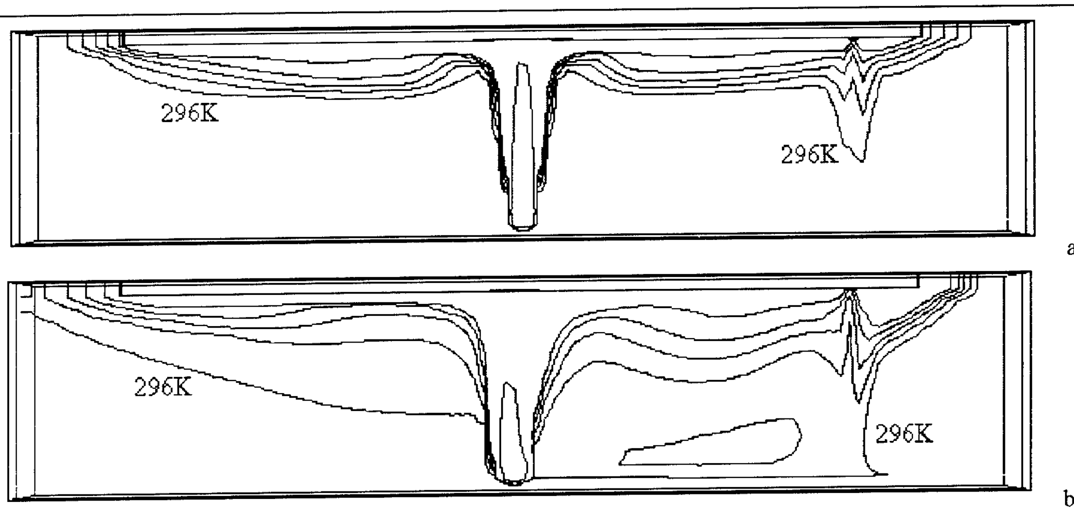


FIGURE 8: Temperature contours (K) along symmetry plane, 1 and 50 seconds after sprinkler activation. Contours start at 296 K and step in 3 K intervals.

The symmetry in the hot layer is disrupted by the sprinkler spray which induces a down draught at its location, resulting in a column of hot air being dragged to the floor (figure 8). One second after sprinkler activation, the beginnings of a descending column of hot air, dragged down by the spray, can be seen.

This approach has been adopted by the FSEG and forms the basis of a spray model for use in aircraft fire applications. The model includes parameters such as flow rates, droplet size, throw angle, orifice size etc. The model is being used as the basis of a European Union funded research project under framework IV known as FIREDASS. The

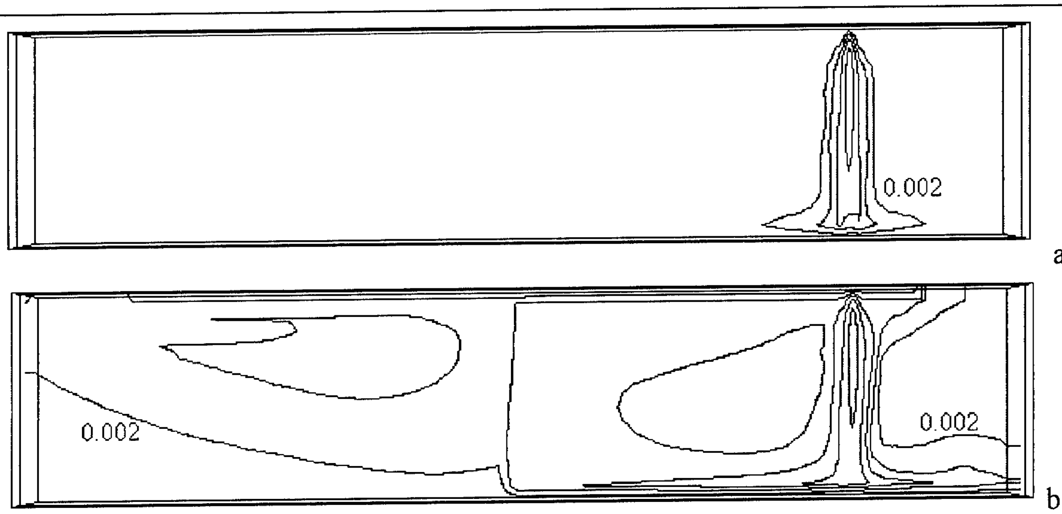


FIGURE 9: Water vapour concentration (kg water/kg of mixture) along symmetry plane, 1 and 50 seconds after sprinkler activation. Contours start at 0.002 and step in intervals of 0.002.

Figure 8 suggests that the gases in the core of the spray cone are cooled relative to the gases on the outside of the cone envelope. This suggestion is substantiated by figure 9 which depicts the water vapour concentration on the symmetry plane 1 and 50 seconds after sprinkler activation. Figure 9 reveals that there is a higher concentration of water vapour in the core of the spray cone. This higher concentration of water vapour is generated through the evaporation of the water droplets. This process requires a large quantity of heat which is extracted from the surrounding hot air. Another important observation to emerge from figure 9b is the manner in which water vapour is distributed throughout the corridor. Water vapour is present on the left side of the fire, remote from the source.

primary purpose of the FIREDASS project is to optimise a water misting replacement for halon extinguishment systems currently used in aviation (aircraft cargo holds) and shipping (machine rooms) applications.

6. CONCLUSIONS

While still requiring further development, fire field modelling has an impressive range of capabilities to offer the aerospace industry. While existing aircraft fire field models rely on imposed fire descriptions, they can be used to describe the spread of fire hazards such as heat and smoke within the aircraft and thus reveal how potentially hazardous conditions develop.

The ability to predict flame spread over solid surfaces and the onset of flashover are two important areas in fire modelling. The model described in this paper was used to simulate the fire development within a compartment in which the ceiling - lined with plywood - was the only source of combustible fuel. In the case of the open compartment fire scenario, the model was able to qualitatively predict behaviour similar to the three stages of fire development - growth and flashover, fully developed and decay. The model was also able to predict the occurrence of a backdraft type phenomenon within a compartment which was originally closed. In this case the model predicted the initial fire growth period, the throttling back of the combustion process and the resulting deflagration when a new opening was suddenly created. The pyrolysis model adopted here appears to provide a promising approach to the prediction of fire spread within enclosures. However, the models must be further developed to include physical behaviour such as charring and downward flame spread and its suitability for other fuels must be established.

The demonstrated ability of fire field models to exploit parallel computing techniques enable these models to be accurately and efficiently employed in large geometries such as B747 and A340 aircraft and their successors. Without this capability, compromises in mesh density and model complexity would be necessary in order to make simulations practical. The linking of aircraft fire models to other predictive models such as water spray models will also be of great benefit to the aviation industry as it strives to find a replacement for Halon extinguishment systems.

7. ACKNOWLEDGEMENTS

Professor E R Galea is indebted to the CAA for their financial support of his personal chair in Mathematical Modelling at the University of Greenwich. The research work described in this paper and originating from the University of Greenwich could not have been achieved without the dedicated efforts of the staff of the Fire Safety Engineering Group and the financial support of our main sponsors the UK CAA and UK EPSRC.

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DISCUSSION - PAPER NO. 7

D. Dierdorf (Question)

Is your code suitable to developing certification methods based on validating droplet sizes and velocity vectors by measurement to demonstrate effective systems?

E.R. Galea - Author/Speaker (Response)

As part of the FIREDASS project, we are performing a series of experiments (without fire) to characterise the spay. This includes spray footprint and particle droplet size distribution. Velocity within the gas phase will also be measured at a small number of sites. This information will also be used to validate the model. As a further point of interest, the UK CAA, which has a role to play in the certification of possible Halon replacements, is a member of the FIREDASS team.

I.R. Hill (Question)

In your Paper, you say that a dry air temperature of 240^0C can be withstood for one minute before incapacitation occurs. The medical and experimental evidence shows that this is not true. Death will occur after a few minutes at an ambient temperature of 100^0C. Deaths have occurred at much lower temperatures.

E.R. Galea - Author/Speaker (Response)

The figures you refer to in my Paper are derived from Fractional Effective Dose models which have been developed by D.A. Purser (see Ref. # 11 in Paper No. 36) and L. Speitel (see Ref. # 12 in Paper No. 36). The heat component in the Purser model is given by:

$$FIH = \frac{t}{e^{(5.1849 - 0.0273*T)}}$$

where t: Exposure time (minutes)
T: Temperature (°C)
FIH: Fractional effective dose of heat

whereas in the Speitel formulation it is given by:

$$FIH = t * 2.4x10^{-9} * T^{3.61}$$

When FIH = 1, the person is incapacitated. Both these formulations are based on correlations and extrapolations of some human exposure data. In the case of the Purser formulation, this data is based on subjects with exposed skin (naked) while the Speitel formulation is based on data using clothed subjects. Thus the Speitel formulation gives higher tenability limits. In the Purser formulation, a one minute exposure to 190°C results in incapacitation (FIH = 1) while in the Speitel formulation, temperatures in excess of 240°C cause incapacitation.

A deficiency in both models concerns the exclusion of the thermal effects due to humid rather than dry air. The incapacitating effects of air with a high water vapour content are more severe than dry air as it reduces heat loss through sweat and delivers more heat to exposed skin. Furthermore, due to its higher heat capacity, inhaled hot air with a high water vapour content can cause more severe

damage to the respiratory tract than dry air at the same temperature. Thus, the limits discussed above could be greatly reduced in humid air.

A. Mulder (Question)

When fine water mist is used, the smoke will be cooled down and will spread through out the room. Must this be seen as a disadvantage of water mist against all its advantages?

E.R. Galea - Author/Speaker (Response)

If the water spray is discharged into an established smoke layer, it will disturb the vertical stratification of the smoke layer and spread it more uniformly throughout the vertical direction. This may have negative implications on the evacuation of passengers from the compartment - however, this is dependent on the absolute smoke concentration. In the example I showed in my presentation, the smoke concentration was quite low, probably resulting in little or no degradation in evacuation efficiency. Furthermore, in practical applications the use of a mist system may result in the reduction of actual burning taking place and hence the amount of smoke produced, compared to the case without a mist system.

J.-M. Buchlin (Question)

On what database did you validate the vapour entrainment within the water spray?

E.R. Galea - Author/Speaker (Response)

Entrainment is not calculated on a macroscopic basis through relationships giving the mass or volume of air entrained given a certain mass flux of water droplets of given diameter distribution. However, the following is done. As with Crowe et al (1977), the drag force exerted by individual droplets upon the surrounding gas is calculated. A force on the gas is equivalent to a momentum source to the gas phase. This momentum source is determined from the force and added to the gas velocity equations. This momentum is distributed through the continuum phase by the normal viscous forces. Consequently, the air in the vicinity of the droplet spay acquires a velocity, i.e. it is entrained. In this way, the mass of air moving is calculated from first principles.

The drag force is given by the modified Stokes law with the drag coefficient of Schiller and Nauman:

$$F = C_D * \frac{A_d}{2} * \rho * (v_g - v_p) \left| v_g - v_p \right|$$

$$\text{where} \quad C_D = \frac{24}{R_e} * (1 + 0.15 * R_e^{0.687})$$

A description of the validation of this relationship is given in my Paper (N. Mawhinney, E.R. Galea, M. Patel, Proceedings INTERFLAM '96); this includes a comparison with a series of experiments conducted at the von Karman Institute in which the velocity of the air entrained by a single, free standing, pendant sprinkler was measured as a function of radius at several distances below the sprinkler head.

Post-Crash Fire Hazards Research

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1. SUMMARY

This paper outlines research funded by the Civil Aviation Authority (CAA) in the UK to explore potential health hazards at aircraft accident sites in the immediate post-crash situation i.e. after rescue and fire fighting has taken place. An initial study considered general hazards, which was followed by work exploring specific problems of composite materials.

The intention was to be able to give best advice to personnel who need to be at an accident site, primarily civil authorities, aerodrome staff and accident investigators. There was also expected to be useful information for fire fighters, although they tend to be generally well protected through the nature of their tasks and do receive regular training in the management of hazards. The potential environmental impact of an accident would also be better understood. Many of the hazards are materials with known characteristics although use (quantities and locations) on aircraft may not be readily determined. Composite materials have less understood post-fire hazards although work to date indicates that current CAA advised precautions are adequate, although further work remains before a definitive position may be established.

Although the research was funded by CAA, considerable help and advice has been given by the Air Accident Investigation Branch and the Royal Air Force.

2. INTRODUCTION

The Safety Regulation Group (SRG) is part of the UK CAA and is the regulatory agency for aviation safety for UK registered aircraft and licensed aerodromes. SRG works within the framework of the Joint Aviation Authorities (JAA) establishing harmonised European regulations. In order to help define appropriate regulations SRG undertakes research on a number (about 80 at the present time) of topics related to aviation safety.

In the early 1990s, SRG became aware that it might be appropriate to issue updated advice to UK aerodromes and others on the safety management of crash sites - experience has shown that accident sites tend to be on or very close to aerodromes. This decision was taken within the environment of an increasing understanding of the potential post-fire hazards from materials used in aircraft construction and an increasing concern (encouraged by legislation) within UK industry generally to provide defined health standards in the workplace. Current CAA advice to minimise the hazard defines a number of precautions including a cordon of 100m radius around the main wreckage with staff to use self contained breathing apparatus and protective clothing (the advice is 300m for military aircraft to afford a level of protection against ordnance hazards). Local assessment is advised to determine if respirable protection may be made by full face masks with filters. This advice has also been disseminated within the UK to Chief Police Offices, Ambulance Organisations and emergency planners.

SRG selected the UK Health and Safety Executive (HSE) to undertake a preliminary hazard study based on published literature. HSE started with an initial list of hazardous materials. Hazards associated with the materials were identified, together with possible fire decomposition products. Additional hazards were identified and advice given on properties and exposure limits. Clearly there are limitations in research of this nature, in particular there was no intention to include cargo within the terms of reference of the study. The materials used in aircraft construction are not required to have a post crash hazard assessment or declaration as part of the aircraft certification, although this situation should not be confused with the most stringent fire safety regulations that must be met, for example in the cabin interior.

Following the study, SRG decided that there was a need to make a more detailed study of the hazards that may be posed by composite materials, increasingly used in aircraft construction. It was recognised that experimental work would be required and it was decided to commission the Defence Research Agency (DRA) at Farnborough to do the work. An additional benefit was that DRA were undertaking a related study for the Ministry of Defence and it was hoped that there would be a useful exchange of information.

3. HEALTH AND SAFETY EXECUTIVE STUDY

The preliminary study was undertaken by the Health and Safety Laboratory, now an agency of the Health and Safety Executive (HSE). The Health and Safety Laboratory is Britain's leading industrial health and safety laboratory, employing some 400 staff, the majority being technical specialists in fields such as fire and explosion behaviour, chemical analysis and biomedical sciences.

The methodology of the study was to consider a known list of hazardous materials likely to be present at an accident site, as distributed to UK aerodromes (Table 1). It was

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

recognised that this list would not be complete and that additions might be made during the course of the study.

HAZARD
Acids-batteries
Alkalines
Arcton 12
Arcton 113
Asbestos
Beryllium + Beryllium Oxides
Bromochlorodifluromethane-fire extinguishers
Bromotrifluromethane-fire extinguishers
Cadmium
Cartridge operated equipment
Chlorobromoethane-fire extinguishers
Composite materials
Coolanol
Depleted Uranium
Dimethylformamide-strobe power packs
Ethylene glycol
Fluorolastomers (Viton)-burnt seals
Freon
Isopropyl Nitrate
Lead
Lithium-batteries
Mercury
Methyl Bromide-fire extinguishers
Polychlorinated Biphenols (PCBs)
Polyvinyl Fluoride (PVF)
Polytetrafluroethylene (PTFE)
Potassium Hydroxide
Radioactive sources
Hydraulic Oil
Strontium Chromates
Sulphur Hexafluoride
Windscreen wash fluid AL-36
Zinc Selenide

Table 1

The chemical formulations for the materials in Table 1 were established where appropriate, providing a more comprehensive list. Following hazard identification, chemical properties, exposure limits, medical effects and control methods were summarised. The study made use of published data and therefore this part of the study was largely a collation exercise.

The intention was then to work with airframe manufacturers to better relate known hazardous materials to likely airframe use, leading to the best possible understanding of potential hazards posed by in-service aircraft. Clearly this would not be able to rigorously define all hazards but given the situation where a wide number of aircraft types from all over the world operate into the UK this was considered to be the most practical approach. It was decided that more data needed to be gathered on composite materials to complete the work.

A longer term goal might be to consider post crash hazards at aircraft certification. It is also possible that airline operators (or more likely, their insurers) may wish to consider this matter when acquiring new aircraft.

4. DEFENCE RESEARCH AGENCY STUDY

The Defence Research Agency (DRA) employs some 8000 staff and is the largest organisation in Western Europe devoted entirely to research and development. It has the principle role to provide the UK Ministry of Defence with expert, impartial advice on all aspects of science and technology. In recent years the DRA's activities have been increasingly directed towards serving other areas of government in both the UK and overseas.

DRA's expertise in structural materials has been concentrated in the Structural Materials Centre (SMC), launched in 1994 and currently employs over 500 staff.

Polymer composite materials are increasingly used in civil aircraft and in any accident these materials may pose a hazard through fibre release, the production of toxic gases and particulates.

SMC was contracted to explore the potential hazards and it was decided to consider a specific modern short-haul public transport jet aircraft and a modern helicopter. An investigation was made of the types of structural composites employed and to keep within budgetary limits, a selection was made of materials for experimental testing as in Table 2 below.

Material	Fibre type	Weave	Resin
APC-2/AS4	AS4 carbon	non-woven	APC (PEEK)
Rohacell foam	n/a	n/a	n/a
Aeroweb A1 nomex honeycomb	n/a	n/a	n/a
Fibredux 914G-E-5	E-GF	non-woven	914
Fibredux 913G-E-5	E-GF	non-woven	913
Fibredux 914K-285	Kevlar	woven	914
Fibredux 916G-1581	Glass	woven	916
Fibredux 913G-1581	Glass	woven	913
Fibredux 913C-833	Carbon	woven	913
Fibredux 913K-285	Kevlar	woven	913
Fibredux 913C-HTA(12K)-5	HTA carbon	non-woven	913
Fibredux 913C/G-HTA(12K)-E	HTA carbon & E-GF	non-woven	913
Fibredux 914C-833	Carbon	woven	914

Table 2

Testing was undertaken in a toxicity chamber to collect information on combustion gases and a cone calorimeter provided burnt samples for the assessment of fibre damage and particulate matter.

A scanning electron microscope was used to examine burnt samples and particulates on the soot filters from the cone calorimeter.

Toxicity testing was based on the Naval Engineering Standard NES 713, using the concentration of 13 standard gases measured by Draeger tubes and combined with a toxic potency weighting quantified by fatal concentration values, defined as fatal to man at a 30 minute exposure time.

The atmosphere in the chamber was also sampled with an absorption tube packed with the absorbent Tenax. Gases were removed for analysis by gas chromatography and mass spectroscopy although many of the identified compounds are not used in NES 713.

In the toxicity chamber, samples were burnt with a flame temperature of 1150°C ± 50°C and the concentration of gases was measured and a toxicity index was calculated. As a guide, the Ministry of Defence defines an acceptance criterion for materials to be used on Royal Navy ships and submarines that the toxicity index at 1150°C should be less than 5. A summary of the toxicity results is given in Table 3 below.

Material	Toxicity
APC-2/AS4	1.18
Rohacell foam	15.03
Aeroweb A1 nomex honeycomb	10.26
Fibredux 914G-E-5	4.75
Fibredux 913G-E-5	4.83
Fibredux 914K-285	9.76
Fibredux 916G-1581	5.54
Fibredux 913G-1581	4.60
Fibredux 913C-833	7.40
Fibredux 913K-285	13.46
Fibredux 913C-HTA(12K)-5	6.27
Fibredux 913C/G-HTA(12K)/E	6.69
Fibredux 914C-833	6.66

Table 3

It is worth noting the particularly low toxicity index for APC-2/AS4 however many organic compounds were identified through the gas chromatography and mass spectroscopy which would contribute to the overall toxicity of the material in practice, thus these figures are only an initial guide. It should be expected that the gaseous hazard would be short term in the post crash situation however in poorly ventilated areas the hazard may persist and pose a threat. Clearly airframe manufacturers should consider using low toxicity composites if other properties permit.

Considering combusted residues, by visual inspection resin was generally entirely consumed although microscopic examination indicated that traces remained. A significant proportion of the fibres in the two materials containing Kevlar decomposed to combustion gases. Examination of the fibres of other materials showed no splits in any of the samples although sharp breaks leaving pointed fibre ends were evident on two of the carbon fibre materials, (the woven carbon material with the 914 resin and the AS4 with the APC-2 resin). There was also pitting damage to other fibres. The soot filters were examined to see if respirable fibres were present but only one fibre was found and may have been as a result of contamination of the filter post test.

5. FUTURE WORK

Structural Materials Centre has been contracted to complete a range of studies building on the first stage of the work. The studies will be complete in early 1997 and the provisional programme is detailed below.

Task 1 will be to explore debris spread at accident sites. This will use data from past accidents and the opportunity will be taken to visit any appropriate crash sites in the period of the study to gather more detailed information (in association with the AAIB and the RAF).

Task 2 will concentrate on fibre release matters. Although the previous work has shown that fibre release did not occur during burning when clamped to a cone calorimeter, this is not the experience at accident sites. Past accidents have shown that fibres may be widely released therefore closer simulation of accident situations will be explored in order to better understand the problem. Materials will be burnt in the following conditions:

a) Undamaged (for reference purposes).

b) Prestressed to failure but not broken.

c) Impacted to barely visible impact damage.

d) Impacted to clearly visible damage

e) Exploration of unsupported edges and holes.

Additional work will be to add to a database for hazards associated with burning polymeric and polymer composite materials.

Studies will be made of samples from crash sites, looking at the evidence for the level of combustion, fibre release and damage.

Further work will be carried out on fire and toxicity tests of composite material samples.

The results will be published as a CAA Paper.

6 ACKNOWLEDGEMENTS

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7 DISCLAIMER

Any views expressed in this paper are those of the author and are not necessarily those of the Civil Aviation Authority.

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AIRCRAFT POST CRASH MANAGEMENT THE ROYAL AIR FORCE APPROACH

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1. INTRODUCTION

The Royal Air Force has the responsibility for the recovery and transportation of crashed or disabled British military fixed wing aircraft - worldwide - and this responsibility is discharged by the Aircraft Recovery & Transportation Flight (AR&TF) at RAF St Athan in South Wales. The corresponding responsibility for the recovery of rotary-wing aircraft rests with the Royal Navy.

Up to the end of 1990, "the nearest flying unit" had a major responsibility for dealing with aircraft crash recovery and we had no specific concerns about health hazards at aircraft crash sites, however, the crash of a Harrier GR5 in October 1990 completely altered our perceptions and approach to what is now almost universally referred to as Post Crash Management (PCM).

2. THE PROBLEM

The Harrier GR5 was our first operational aircraft containing significant amounts of composite materials - mainly carbon fibre composites (Figure 1). On 17 October 1990 a Harrier GR5 overflying Denmark suffered an engine failure, the pilot ejected safely and the aircraft crashed on Danish open farmland, luckily doing no damage and causing no casualties. There was an intense fire which was extinguished by the local fire service and in due course the RAF recovery team arrived to recover the wreckage and specifically to retrieve the engine and engine management systems.

The RAF team were aware of a potential health hazard from the carbon fibre composites and they came prepared - or so they thought - with enhanced protective clothing including facemasks and goggles, they also sprayed the crash site in an effort to damp down the dust and ash resulting from the fire. Unfortunately the damping down was only partially successful and the masks and goggles were not totally compatible. Consequently, after 48 hours of rapidly increasing discomfort - sore throats, eyes and chests - combined with rapidly developing skin irritations - the site had to be temporarily evacuated until more effective protective measures could be effected.

The main problem proved to be the shattered and burned composite materials. The shattered fragments had extremely sharp edges and had to be handled with care, but far more difficult and potentially hazardous were the very small, light and sharp strands of carbon fibre which had been released from the burned epoxy resins and were now blowing about the crash site like dust. These "needles" (Figure 2) were typically 2-4 microns in diameter, which, on contact with the skin caused minute "needle stick" punctures and, because the "needles" were often extremely dirty, the resulting wounds quickly become infected. It was clearly very important to also prevent the inhalation and ingestion of these fibres.

Once the root cause of the problem had been identified and understood, the RAF team were able to obtain much more effective protective clothing and to adopt controlled site procedures of washing and decontamination using recognised "clean" and "dirty" area disciplines. Fortunately, once these measures were in place the acute health problems disappeared and did not recur, but the lesson was well learned - the potential health hazards of burned carbon fibre composites, or MMMF (Man Made Mineral Fibre) as it is now often called, must not be underestimated. During this time an RAF Environmental Health Team

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carried out a number of surveys of the crash site and, as well as the MMMF and the other expected military hazards, they identified small quantities of organic compounds including Naphthalene, Phenols and Alcohols as well as metals such as Titanium, Beryllium, Vanadium, Chromium and Manganese. All of which can be regarded as irritant, narcotic and possibly carcinogenic. Admittedly the quantities were small, but how small does a hazard have to be before it can be ignored?

So much for lesson one - but lesson two happened about seven months later when another "carbon fibre" Harrier crashed into some German woodland. As often happens the local fire service arrived on the scene and extinguished the fire before the RAF team arrived, but when the German firemen saw the RAF personnel in their enhanced protective clothing they were naturally concerned - "Why are you dressed like that ?" "What hazardous stores was the aircraft carrying ?" and finally the crucial question "Why did nobody warn us ?" Luckily they suffered no ill effects.

Clearly three factors had come together to give us a significant problem:

a. The increasing use in aircraft manufacture of materials which may present a hazard at a crash site - particularly when burned.

b. Our increasing awareness of the problem - we could no longer plead ignorance.

c. Increasing Health & Safety and Pollution legislation coupled with "Duty of Care". This applied not only to the servicemen on the site but also to any civilian who may be involved - either as part of the emergency services or perhaps inadvertently.

In considering the matter of "responsibility" we assumed that, as the equipment (aircraft) operators, Duty of Care at the crash site lay primarily with the Royal Air Force. However, there was also a clear responsibility with the aircraft manufacturers to inform us of the materials contained in the aircraft and their potential hazards - particularly when burned.

3. SO WHAT DID WE DO?

We liaised closely with the aircraft manufacturers and the engineering authorities for each of our aircraft to produce lists of hazardous materials, and also information on materials which could become hazardous when burned.

We compiled this information into a computer based "Hazard Database".

We reorganised our resources. The role of "the nearest RAF Unit" was restricted to providing assistance with immediate firefighting and lifesaving if near enough. All our specialist recovery and salvage teams were now concentrated together forming AR&TF at RAF St Athan in South Wales. Thus all skills and experience were centralised.

AR&TF have four Aircraft Recovery Officers, one of which is always on immediate standby to respond to a crash. AR&TF have sufficient manpower to provide three full recovery teams.

We revised the way in which other specialist teams such as Environmental Health and Satellite Communications (SATCOM) could provide rapid and effective support to AR&TF when required.

We revised our procedures and published new sets of Orders and Instructions. We produce a comprehensive Post Crash Management Report after each crash and regularly review our procedures in the light of these reports.

We adopted a vigorous policy of liaising regularly with the civil emergency services. Not only Fire, Police and Ambulance, but

also with any other interested agency such as Emergency Planning, Environmental Health and National Rivers Authority.

We also liaised with other Airforces, with the CAA (Civil Aviation Authority) and with the AAIB (Aircraft Accident Investigation Branch).

We identified four levels of possible hazard on site and specified the personal protective clothing required for each level.

We identified, trialled and procured new on site equipment such as rapid erection tentage, portable showers and digital mapping instrumentation.

We developed effective on-site spraying techniques to reduce the airborne particle hazard.

We liaised closely with the Royal Navy who follow our procedures when dealing with rotary wing aircraft.

We adopted the policy of (as far as is practical) removing all trace of aircraft wreckage and potentially harmful debris to the satisfaction of the appropriate civilian agencies.

4. WHERE ARE WE NOW?

Our new policy and procedures are working well. We formally review the procedures every 6 months in the light of experience and implement any necessary changes to procedures or equipment.

As well as dealing with military crashes which average about 8 each year, we are frequently called to assist with civil air accidents and these calls average about 10-15 each year. This results in AR&TF dealing with about 20 crashes in a year and the accumulating experience is proving to be extremely valuable.

Our original hazard database has developed into a comprehensive and useful tool.

Our liaison work with the civil emergency services and other civil agencies is expanding, the benefits from improved lateral communication are clear.

5. THE WAY AHEAD

Research into PCM hazards and protection against them will continue. Common agreement between the military and civil agencies on these issues and on data presentation would be very useful.

We will continue to review and refine our procedures, again common agreement on basic procedures between the military and civil agencies would have significant advantages.

To be effective, procedures need to be practised regularly with all the participating agencies, but realistic full-scale exercises are difficult and increasingly expensive to organise. There is perhaps scope for initiatives with computer simulation and even virtual reality techniques
Experience is one of the best teachers and we can all learn from the experience of others. PCM Reports, both military and civil should be shared. It is our experience that reference to classified or sensitive issues can easily be avoided.

Component and materials manufactures normally supply Hazard Datasheets to the aircraft manufacturer covering any potentially toxic materials, but frequently this information is not passed on to the aircraft operator. Additionally the aircraft manufacturer is often unaware of the specific materials contained in major components or aircraft sub systems, and seems reluctant to accept the responsibility of collating all the hazard data and advising the aircraft operator. This problem must be addressed but the answer will not be easy.

The use of potentially toxic materials in both military and civil aircraft is increasing rapidly. Manufactures must acknowledge the problem and strive towards safer materials. The threat is not only against the aircraft passengers, crew, and the

emergency services - it now also includes densely populated urban areas.

The interest being shown by the aviation insurance industry is increasing.

6. IN CONCLUSION

The Royal Air Force has acknowledged the potential toxic hazard posed by the crashing and burning of current military aircraft and has established an effective organisation to deal with these problems. However, the amount of potentially toxic composite materials in a large modern civil aircraft greatly exceeds that in an RAF Harrier, and the toxic hazard problems suffered by us in Denmark in 1990 would pale into insignificance when compared to the threat posed by a civil aircraft crash into a densely populated urban area. At the same time, Health & Safety and anti-pollution legislation is becoming ever more comprehensive. Only by working together, acknowledging our responsibilities and developing a common approach will we begin to address this much greater problem.

John Andrews
October 1996

Figure 1: Composite materials in Harrier GR5.

Figure 2: Magnified view of carbon-fibre "needles".

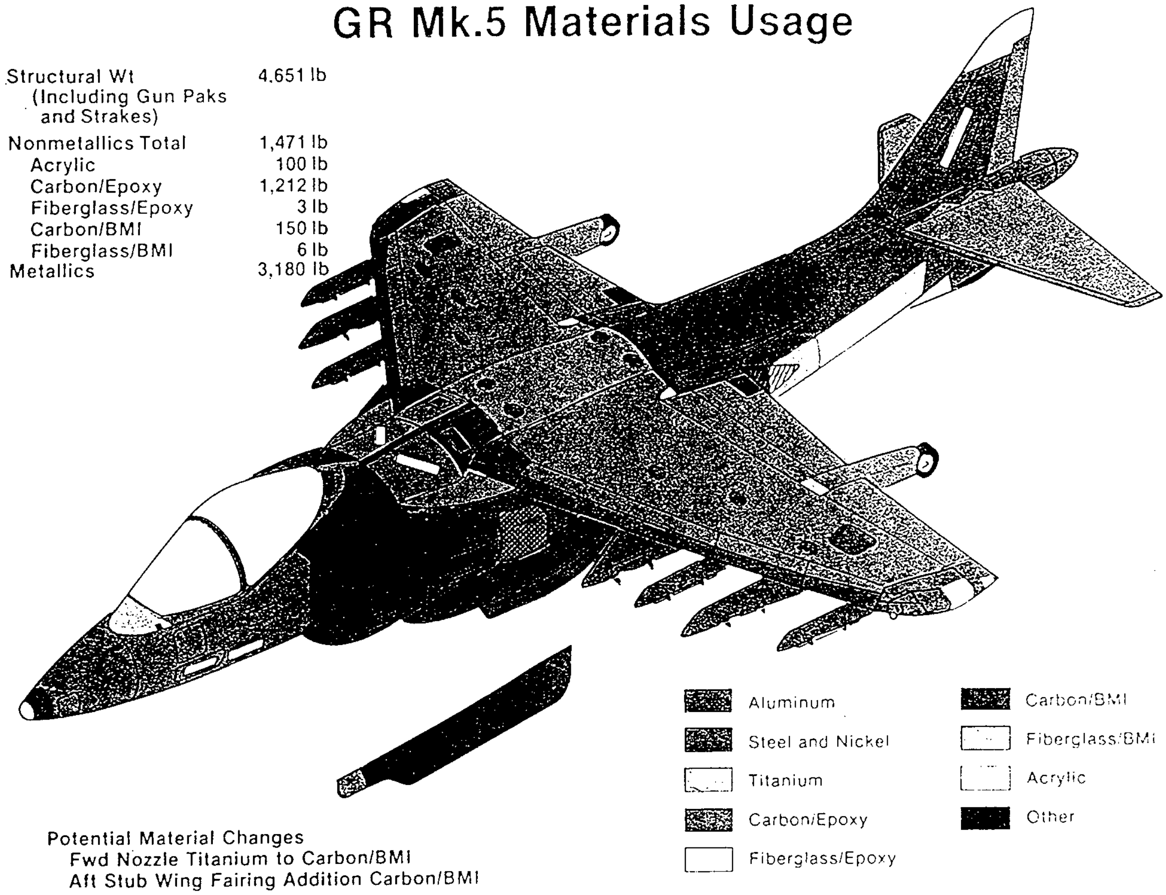

Figure 1: Harrier GR5

Structure weight 2115 kg
Composite weight 669 kg (31.6%)

Composites primarily in flying surfaces and forward fuselage.

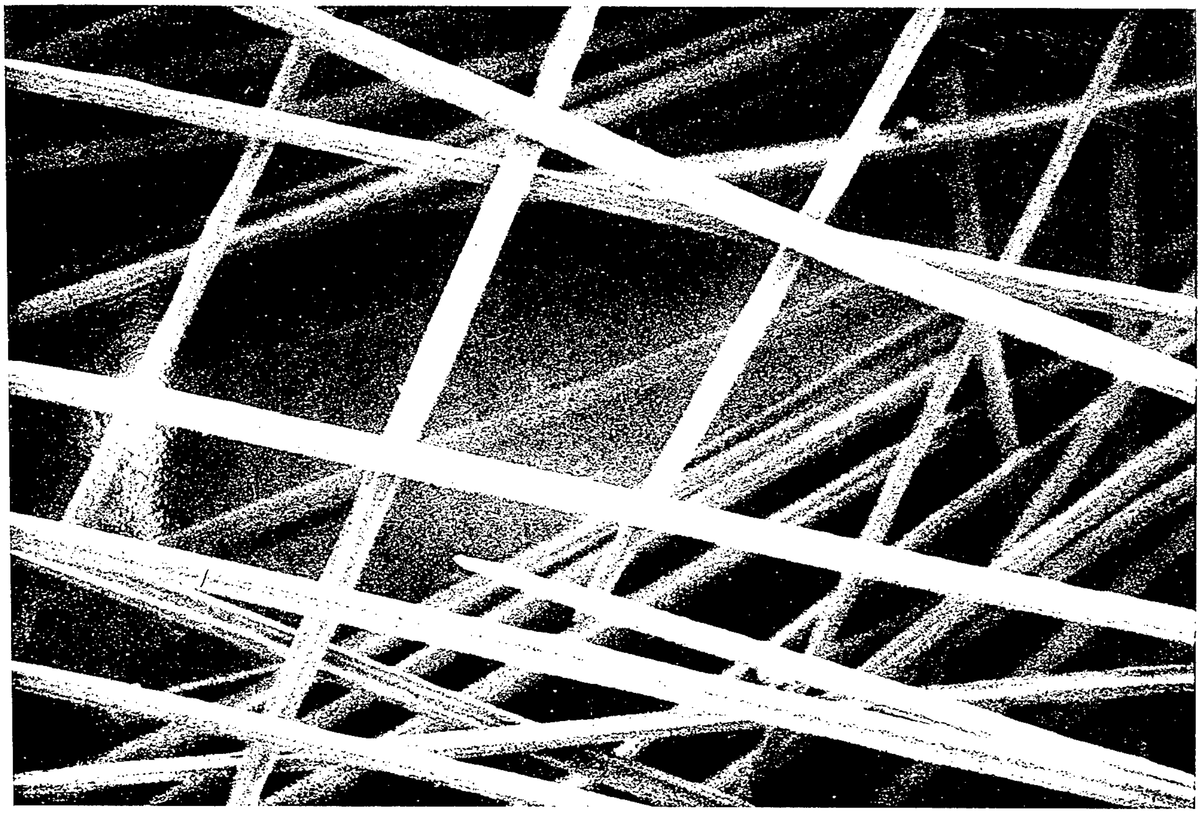

Figure 2: "Needles" from burned carbon fibre composites. Diameter 2 to 4 microns.

FIRE SAFETY CONCEPT FOR A MODERN COMBAT AIRCRAFT

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INTRODUCTION

Engine an auxiliary power unit fire detection and extinguishing systems are now standard equipment on modern aircraft and have been installed for many years. The majority of these utilise continuous thermal detection systems which will respond to changes in temperature within the protected compartment. More recently the latest generation combat aircraft have used optical detection systems in place of these traditional thermal detection methods. This offers weight saving and much faster response to fire.

Protection of other areas, such as fuel tanks and dry bays, is fast becoming essential as the combat threat from even small arms projectiles increase.

It is fundamental to the operational role of combat aircraft that they are exposed to high levels of risk, particularly that resulting from hostile action. A wide range of countermeasures can be, and are, taken to minimise the probability of an aggressor succeeding in damaging the aircraft, but these measures cannot be totally successful and the consequences of sustaining damage must be considered.

Studies have been carried out to determine which areas of the aircraft are most susceptible to combat threats and which areas or systems are most likely to cause aircraft damage or loss from fire and explosion if combat damage was sustained.

The fuselage, tail and wing were not surprisingly, the areas which suffered the most combat hits contributing to more than 70% of incidents.

Fuel and hydraulic systems were involved in almost 80% of combat losses in fighter aircraft and similar figures were reported for transport aircraft.

FUEL TANKS AND DRY BAYS

In considering the risk of fuel fire or explosion, the first area of concern is the fuel tanks. Typically these may account for 25% of the presented area of the aircraft, and are correspondingly vulnerable to penetrating weapons.

Dry Bays, which are often adjacent to fuel tanks, may contain fluid lines, electric wiring and equipment containing combustibles and possibly gun and ammunition installations. There is a wide variation in the characteristics of dry bays - location, size, shape and the type of equipment that they many contain. They are enclosed , but not sealed, and will experience ventilation due to design, changes in ambient pressure or due to combat damage.

The ability of these parts of the airframe to withstand internal explosion pressure is highly variable, and is dependant upon factors including their size, shape and construction. Fuselage tanks in fixed wing aircraft may survive gauge pressures of well over 1 bar, and wing tanks even more, while in helicopters some tanks may fail at 0.3 bar and lightweight skin panels at still lower pressures.

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COMBAT EXPLOSIONS

In the simplest case an explosion develops from a point source of ignition remote from the vessel walls, and a spherical combustion wave propagates away from this point through a homogeneous fuel air mixture. The initial rate at which the fireball expands is dependant upon the burning velocity of the mixture, which, at a given altitude, is determined by the fuel type and temperature and its concentration in the ullage space. The quantity of fuel burnt in a given period of time is thus independent of vessel size, and the rate of rise of explosion pressure is, therefore, greater in a smaller vessel volume.

As the expanding fireball approaches the walls of its container its initial spherical shape is perturbed and it tends to assume the shape of the vessel. If the initial pressure in the vessel was 1 bar, and it remained fully sealed, a peak pressure of about 9 bar will be reached.

In general the development of combat fires and explosions is more complex than this simple case, in particular because of their source of ignition. Combat aircraft are exposed to a wide range of threats, for example incendiary round of various types and calibre, and inert metallic fragments from missile warheads. A single fragment passing through a fuel tank would represent a possible ignition source, but the more likely ignition points are the hot areas of the tank wall where the fragment entered and left the compartment: from each of these points a fireball would develop with hemispherical symmetry. Some types of incendiary round may leave a trail in incandescent material along their path, which would act as a line ignition source leading to cylindrical fireball growth. Other types of round may generate a shower of hot particles, each of which may cause point ignition; a multiple fragment strike will have a similar effect; and at least during the early stages of the event, the effects of these growing fireballs are additive.

A further effect of projectile strike, if it occurs below fuel level, is to generate a spray of atomised fuel and to induce a high level of turbulence. Both these effects will enhance the severity of the fire.

If impact occurs on a wing surface, for instance, it may be only the fuel tank which presents an explosion risk. If, on the other hand, penetration occurs on a leading or trailing edge or on the fuselage, the projectile must first pass thorough the adjacent compartment. In doing so it leaves behind potential ignition sources in the hot spots where it pierced the walls of the bay and any internal fittings. If entry to the tank then occurs below fuel level, hydraulic shock forces a spray of fuel from the entry point into the adjacent bay and gives rise to a second area of high fire risk.

The manner in which the fire or explosion develops is dependant on a large number of variables. However, it appears that generally the developing fire or explosion exceeds the maximum safe pressure within an extremely short time, leaving as little at 20 milliseconds available for a protection system to detect and suppress the incipient fireball in a fuel tank and experiments have shown that similar response times are necessary in protection dry bays.

The consequences of unsuppressed events of this type are likely to be explosion of the fuel tank or dry bay , disruption or loss of flight surfaces and systems, spread of the fire to adjacent areas, and high probability of losing the aircraft.

DETECTION

There are a number of means of detecting fires which are widely used in less exacting applications, but optical sensors provide the only method of flame detection rapid enough for these circumstances. Flames are strong sources of radiation, and it is not difficult to devise a detector which responds to their presence. Unfortunately, it must be assumed that the system will also be exposed to other radiation sources to which it must not respond, typical of which are sunlight and inspection lamps.

Immunity from such false alarms can be ensured by careful selection of the wavelengths at which the detector operates. There are critical points, within both the ultraviolet and the infrared which will not respond to sources other than flame.

For Dry Bay applications IR detectors are the favoured choice. They can be designed to retain a high degree of false alarm immunity and to respond to penetration of the aircraft by an incendiary round in less than 1 millisecond. Such detectors are being applied to a number of state-of-the-art airframes. They operate primarily at a wavelength of 4.4 microns using

a thermopile fitted with an interference filter. A second channel in the rear IR is also used to improve immunity to non-fire stimuli. The 4.4 microns wavelength is chosen because there is a strong emission band centred there due to radiation emitted by excited carbon dioxide molecules, a major product of hydrocarbon combustion.

Current explosion detection systems, as applied to the F/A-18 E/F and the F-22 may use anything between one and seven sensors in each protected bay. There may be up to fourteen sensors in a single aircraft. The sensors weigh from 150 to 400 grams depending on whether they include their own power supply and firing circuit or operate through a separate control system. They incorporate built-in through-the-lens optical test and are able to withstand temperatures of over 100°C and vibration levels over 30g RMS.

FIRE AND EXPLOSION SUPPRESSION

Fire, or explosion, is an exothermic combustion between a fuel and oxygen, ignition supplies sufficient energy to the system to activate this reaction, and the energy liberated by the combustion them makes the process self-sustaining.

There are a number of ways to prevent combustion:

- eliminate the oxygen;
- remove the thermal energy which sustains the reaction;
- over-enrich the mixture so that the concentration of flammable vapour exceeds the upper explosive limit;
- introduce a physical barrier between the fuel and the sources of oxygen or energy;
- interfere with the combustion chain reactions by introducing either materials which physically absorb these intermediates, or chemicals which react with them.

Each of the above methods has been successfully used in the suppression of fires. Nitrogen inerting systems and carbon dioxide extinguishing rely on oxygen depletion, and, at altitude, depressurisation is widely used to minimise fire risk. Extinguishing foams form a barrier isolating the fuel. The fibrous structures which are used to foam-fill fuel tanks operate as a combination of thermal absorber and physical barries.

Other methods are more suited to high speed active systems where an extinguishant is injected following detection of an incipient fire these include:

- **Pentane** - has been used to over-enrich the fuel tanks of combat aircraft; it offers weight savings, and also the advantage that the fuel is not contaminated by materials which could clog or corrode pipework and filters or affect its combustion performance in the engine.

- **Water and Powder** - these extinguishants operate by thermal abstraction, however, water is not an effective suppressant of gas phase combustion and is not used in protecting fuel systems.

- **Halons 1011 and 1301** - a family of halogenated hydrocarbons, combine thermal abstraction with chemical scavenging of reaction intermediates.

Delivery of extinguishant must obviously be extremely fast to ensure the necessary rapid suppression of the developing fireball. Different types of hardware are appropriate for use with low-boiling liquids such as Halon 1301, high-boiling liquids like pentane or Halon 1011, and powders.

- **Pressure Vessels** - Halon 1301, as gas at room temperature, is stored highly pressurised as a liquid in a pressure vessel with a valve which is explosively opened, typically in one or two milliseconds.

- **Hemispherical Vessels (Liquids)** - less volatile liquid extinguishant can be stored un-pressurised and the container can be lighter. The vessel is operated by an electric detonator located in the centre of the vessel. When fired the hydraulic shock propagates through the liquid, fractures the frangible hemispherical dome, scored to "petal" open, and thrusts the extinguishant out of the container as an atomised mist. This is an extremely rapid delivery method;

- **Conical Vessels (Powders)** - powder does not transmit hydraulic shock and therefore the material is stored, un-pressurised, in an open conical container, retained by a thin foil. A high speed cartridge at the apex is fired to produce a puff of gas which bursts the foil an disperses the powder into the protected space. Again very rapid.

More recently newer, more novel approaches have been taken towards the suppression of Dry Bay explosions.

Some work at Walter Kidde Aerospace in the United States has concentrated on a system called PALAS. (Pyrotechnically Augemented Liquid Agent System).

PALAS is a development of a high pressure liquid agent atomising concept which uses solid propellant gas generator technology to produce a rapidly dispersing, finely atomised, cloud of liquid droplets. This is achieved by discharging the agent at high pressure, typically greater than 1000 psing. This approach is suitable for both "line of sight" explosion suppression applications and in highly cluttered environments such as aircraft dry bays. In an aircraft dry bay "line of sight" may not always exist and it is important to maximise the three dimensional dispersion potential of the most effective HFC agents which have boiling points similar to halon 1301.

PALAS takes advantage of solid propellant gas generators in two ways.

- Firstly it uses the high discharge pressure to atomise the agent close to the discharge nozzle.

- Secondly it uses a fraction of the hot gas produced to impart heat into the agent so that the droplets will flash vaporise. The maximises the dispersion characteristics of the agent.

The approach effectively generates a high heat capacity gas which has superior extinguishing performance in comparison with inert gases. It eliminates the tendency to produce over pressure in the protected volume due to the rate of discharge of the extinguisher.

Work is also being carried out on the use of Solid Propellant Gas Generators on their own ie without the additional effect of the extinguishing agent. This approach relies on burning a solid propellant that produces an exhaust which will suppress the fire. The exhaust is free from environmentally unacceptable gases and therefore overcomes the disadvantage of halons.

A number of different approaches are being evaluated and these include different formulations of the propellant itself together with a number of different variations with regard to the packaging of the propellant itself.

The work on both design approaches is in its infancy but both have been shown to be very effective in small scale testing. Further work will be required before these concepts can be incorporated into a fully productionised product.

ULTRA VIOLET FLAME SENSORS

Ultra violet flame sensors, those operating in the 200-280nm range have been used for flame detection over many years.

Because of its glass and metal construction the UV sensor is intrinsically highly rugged and is able to withstand extremes of temperature. One application which takes advantage of these features is in engine protection. The flame detectors must be located immediately adjacent to the engines, and may thus be exposed to continuous ambient temperatures levels up to 200°C, an environment in which few electro-optic devices can survive and operate. The ability of UV sensors to do so make them a viable alternative to the current generation of thermal detectors. However, an important additional advantage is gained; if, due to some disruption within the combustion zone of the engine, the gas flow pattern is perturbed, very hot flame can impinge upon the metal casing and will rapidly burn through it.

UV flame detectors can provide a warning if such a 'combustor can burn through' event occurs and, unlike thermal detectors, can be relied upon to do so sufficiently rapidly to allow action to be taken before the torching flame can penetrate adjacent fuel tanks or damage other critical equipment. It is this benefit which is leading to the selection of systems of this type for the new generation of advanced military aircraft.

A UV flame detection system recently designed for engine protection in a fighter aircraft programme is the first usage of optical sensing as the primary (rather than a backup) means of fire sensing in the application. Eight sensors are located near to the front of the engine viewing towards the rear (to minimise the risk of accumulating contamination). The sensors each weigh some 150g and are able to withstand temperatures up to 190°C and vibration levels of 30g rms. They are arranged in four pairs, and, for reasons of redundancy, one of each pair is powered by one of two power supply units and one by the other. These weighing about 350g each, are located in bays near the engines but with less demanding environments, generate the high voltage - some 300v - required to power the UV sensors, and interface with the on-bord computer to report fires or system faults. A conventional fire extinguisher is operated manually if a fire alarm is generated. Additional reasons cited by user for the selection of the optical approach include maintainability, both of the sensor itself, which is easier to fit and remove than a continuous sensing element, and of other accessories in the vicinity, to which access is less affected. Thermal sensors can respond to overheat conditions as well as to fire, which is not currently possible with optical systems, and in this installation an overheat detector is also fitted at the rear of the engine.

A second application also relates to high performance jet engines. In many military aircraft, when extra thrust is required over a short period for take-off or trans-sonic acceleration, additional fuel is injected into the engine outlets to produce the extra power needed. Before fuel injection can safely commerce, it is essential to ensure that the pilot flame which provides the ignition source is alight, and it is a UV detector which is used to monitor the flame. A typical Reheat Ignition Monitoring System might consist of two sensors per engine with a remotely located power supply unit. A typical sensor would weight 300g and withstand temperatures up to 200°C and vibration levels of over 20g rms.

As you can see much work has gone into the research and development of new fire protection systems for modern military aircraft. The results provide greater survivability for both the aircraft and therefore the crew. The research will continue and we will undoubtedly see some of this technology spin off into the civil market place.

WATER SPRAY SYSTEM DEVELOPMENT AND EVALUATION FOR ENHANCED POSTCRASH FIRE SURVIVABILITY AND IN-FLIGHT PROTECTION IN CARGO COMPARTMENTS

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1. SUMMARY
This paper describes full-scale fire tests conducted by the Federal Aviation Administration (FAA) to evaluate and optimize water spray systems in two specific aircraft fire safety applications. The first application was an onboard cabin water spray system designed to improve postcrash fire survivability. The goal is to suppress a severe cabin fire, initiated by a large external fuel fire, in order to improve the available time for passenger evacuation. The second application was a cargo compartment water spray system for the purpose of suppressing and controlling in-flight cargo/luggage fires. In this case, the water spray system must suppress and contain a worst-case, deep-seated fire for as long as 180 minutes, or until an airplane can be safely landed.

2. INTRODUCTION
Although aircraft crashes occur very infrequently, the life safety consequences of a postcrash fire are of great concern because of the potential involvment of large quantities of flammable jet fuel, the use of polmeric materials to line and furnish the cabin, and the problems associated with the rapid evacuation of a large number of passengers from a confined environment.

The goal of enhanced postcrash fire survivability is twofold: (1) additional available time for passenger evacuation by reducing cabin fire hazards, and (2) greater evacuation rate of passengers. Improvements in postcrash fire safety attaining these goals have been achieved in recent years (Sarkos, 1989), including the installation of more fire resistant cabin materials, based on stringent fire test standards developed and adopted by FAA. The FAA has strived to develop further improvements in postcrash fire survivability in a joint program with the United Kingdom (U.K.) Civil Aviation Authority and Transport Canada to develop an on-board cabin water spray fire suppression system. The baseline water spray system was designed in the U.K. by Safety Aircraft and Vehicles Equipment, Ltd. (SAVE). It basically consisted of a large number of small nozzles, mounted throughout the ceiling, which discharged a fine water spray (mean droplet diameter of about 100 microns) throughout the length of the cabin for a period of 3 minutes (Whitfield, et al, 1988).

The test arrangement for the cabin water spray tests simulated a survivable aircraft crash involving fuselage exposure to an external fuel fire. The fire source was an 8-by-10 foot pan of burning jet fuel which had been shown previously to be representative of the thermal threat created by a large fuel spill fire. The discussion in this paper will be limited to a typical scenario comprised of a fuel fire adjacent to an opening (simulated rupture) in the test fuselage the size of Type A door (76 by 42 inches). A variable speed exhaust fan in the front of the fuselage created a draft inside the cabin, allowing the degree of fuel fire penetration through the hole and the resultant severity of the fire inside the cabin to be varied. Good control over the fuel fire conditions were maintained because the tests were conducted inside a building, assuring test repeatability. The 8-by-10 foot pan fire tests were conducted with both a narrow-body fuselage and a wide-body fuselage. The former is a surplus B-707 airplane while the latter is a 130-foot-long hybrid consisting of a 40-foot DC-10 section married to a 90-foot cylinder. Similar tests with a smaller fuel fire were conducted in a Metroliner commuter aircraft test article.

Aircraft cargo compartments are protected with Halon 1301 total flooding fire suppression systems. Since the production of halon ceased in developed countries on January 1, 1994, as specified by an international agreement called the Montreal Protocol, the future availability of halon for aviation is uncertain. Therefore, the FAA has a program to evaluate replacement and alternative agents/systems, such as water spray, in cargo compartment and other aircraft applications for the purpose of developing certification criteria for those agents deemed acceptable (FAA, 1993). A cargo compartment water spray system could also trade-off the weight penalty associated with a cabin water spray system.

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The cargo compartment water spray tests were conducted in the lower forward compartment of the wide-body test article. The volume of the cargo compartment was 2300 cubic feet and the leakage rate was 85 cubic feet per minute, or one air change every 27 minutes.

3. EFFECTIVENESS OF CABIN CONTINUOUS WATER SPRAY SYSTEM

Narrow-Body Test Article. A plan view of the narrow-body test article is shown in figure 1, indicating the fuel pan location, continuous (SAVE) water spray system nozzle arrangement and location of instrumentation and cabin materials. The water spray system consisted of 120 nozzles which discharged 72 gallons of water over a period of 3 minutes. Instrumentation consisted of thermocouples, smoke meters, gas analyzers, gas sampling equipment, calorimeters, and photographic and video cameras. A 24-foot-long section of the test article, centered at the external fire pan, was outfitted with 5 rows of passenger seats, ceiling panels, stowage bins, sidewalls, and carpet. All materials were compliant with the current FAA fire test standards (Sarkos, 1989). A similar test setup was utilized in the wide body tests described later in the paper.

Initially, a zero ambient wind condition was simulated by not operating the exhaust fan. With the absence of flame penetration through the fuselage opening, the fire exposure of cabin materials was dominated by intense thermal radiation. The results of the zero wind tests, with and without water spray, are shown in figure 2. The shaded areas in this and subsequent figures show the range in measurements at a particular fuselage station. In all cases, the highest readings were at the highest locations, and the readings decreased the closer the measurement location was to the floor. Temperature was measured at 1-foot increments from a location 7 feet high (slightly below the ceiling) to a location 1 foot above the floor. Smoke was measured at three heights: 5 feet, 6 inches; 3 feet, 6 inches; and 1 foot, 6 inches. All gas measurements were at 5 feet, 6 inches and 3 feet, 6 inches.

Figure 2 exhibits a rapid rise in temperature and toxic gas production and a decrease in oxygen concentration at approximately 5 minutes in the test without water spray. This behavior indicates the development of a flashover condition at 5 minutes. However, when water spray was used, survivable conditions prevailed for the entire 7-minute test duration. The time interval of actual water spray discharge was from 15 seconds until approximately 195-200 seconds into the test. Therefore, in addition to the reduction in cabin fire hazards during the water spray discharge, there were notable improvements in the cabin environment after the discharge was completed.

Survival time was calculated from the measured hazards by employing a fractional effective dose (FED) model (Speitel, 1995). It assumes that the effect of heat and each toxic gas on incapacitation is additive and that the increased respiratory rate due to elevated carbon dioxide levels is manifested by enhanced uptake of other gases. The FED plot in figure 2 shows incapacitation occurred at 5 minutes without water spray discharge, corresponding to the time of flashover. Discharge of water spray prevented flashover within the 7-minute test duration and maintained a survivable environment within that increment (FED<0.1 at 7 minutes). Therefore, the increase in survivability provided by water spray discharge was much greater than 2 minutes.

A "moderate" wind scenario was devised, by operating the exhaust fan to induce fuel fire flame penetration through the fuselage opening, in order to create a more severe fire threat than imposed by the zero wind condition. Figure 3 shows the results of those tests. The profiles are quite similar to the zero wind test (figure 2) but are transposed earlier in time by about 2 minutes. Flashover occurred between 150 and 180 seconds without water spray. With water spray, flashover occurred much later (about 300 seconds) and with less intensity (lower temperature rise and gas production). The FED plot shows that the increase in survival time was 215 seconds. Figure 3 also shows that water spray is highly effective in removing water soluble acid gases such as hydrogen fluoride.

The water spray system was also evaluated against a "high" wind scenario. In this case, the fuel fire flames penetrated across the ceiling practically to the opposite side of the cabin. The fire was so severe that it overwhelmed the water spray, and it became necessary to terminate the test after only 60 seconds. The high wind test further illustrated that the benefits of fire safety design improvements are highly dependent upon the fire scenario, and for some very severe scenarios it is virtually impossible to improve survivability by design changes.

Wide-Body Test Article. In the wide-body test article, the SAVE system consisted of 324 nozzles, arranged in 5 rows along the length of the fuselage. A quantity of 195 gallons of water was discharged over a period of 3 minutes. A "moderate" wind condition, causing fuel fire flame penetration through the fuselage opening, was utilized to evaluate the effectiveness of water spray in the wide-body test article. Figure 4 shows the result of those tests. As in the narrow-body tests, significant reduction in cabin temperatures and toxic gas levels were evidenced during the water spray test. Of some concern is the light transmission profiles reflecting the reduction in visibility due to smoke. For more than half the test duration, because the water spray tends to lower the ceiling smoke layer, there is a greater reduction in light transmission while the water is being discharged. Apparently, the amount of smoke particulate removal or "washing out" by the water spray is more than offset by the lowering of the smoke layer. Later, however, the

reduction in light transmission with an unabated fire becomes more significant.

The FED curve indicates a loss of survivability at 215 seconds without the water spray system. Examination of the temperature and gas levels. particularly oxygen concentration (not shown), indicates the onset of flashover at about 210 seconds. With water spray, flashover was prevented over the 5-minute test duration and the cabin environment (away from the fire source) remained survivable. On the basis of the FED calculation, the improvement in survival time at the end of the test was 85 seconds, and would likely have been considerably longer, perhaps 2-3 minutes, had the test not been terminated.

4. OPTIMIZATION OF CABIN WATER SPRAY SYSTEM

Because of payload, weight penalty is an overriding consideration in aircraft design. The weight penalty associated with the SAVE system is somewhat excessive, if not prohibitive. The concept of a zoned system divides an airplane cabin into a series of water spray zones. Discharge of water within each zone is independent of the other zones and triggered by a sensor within the zone. In this matter the quantity of water discharged is dictated by the presence and spread of fire, eliminating the ineffectual and wasteful discharge of water away from the fire as in the SAVE system (Marker, 1991). A zoned system was designed, tested and optimized in the narrow body test article.

Each zone was 8 feet in cabin length. Four spray nozzles were mounted at the cabin periphery in each of the two boundary planes, with the spray discharge directed toward the center of the zone. Based on preliminary tests, a temperature of 300 degrees Farenheight (F) was selected to manually activate water discharge. The temperature was measured at the center of the zone about 6 inches below the ceiling . Three types of nozzles were evaluated; low, 0.23 gallons per minute (gpm) (SAVE nozzle); medium, 0.35 gpm; and high, 0.50 gpm. A more severe simulated wind condition than employed previously was used as the test condition.

The calculated FED profiles from the initial series of optimization tests are shown in figure 5. The SAVE water spray system, discharging 72 gallons of water, increased the survival time by 110 seconds. More importantly, the medium and high flow rate nozzles, discharging a total of only 24 gallons of water, increased the survival time beyond the SAVE system by about 55 seconds and 35 seconds, respectively. The improvement provided by the higher flow rate nozzles is apparently due to the application of larger quantities of water where it is needed most -- in the immediate fire area. An interesting result is that the medium flow rate nozzles provided more protection than the high flow rate nozzles. A possible explanation is that the discharge time was longer with the medium flow rate nozzles; i.e., 180 seconds versus 140 seconds.

In an attempt to optimize the zoned system, 9 zoned water spray tests were conducted, employing 4 water quantities and 3 nozzle flow rates. The results are summarized in figure 6 in terms of the additional available escape time beyond the baseline test without water discharge. The results of the SAVE test are also shown (108 seconds additional escape time). Each of the zoned tests provided a significant improvement in the additional escape time, which was greater than the improvement with the SAVE system in 5 of the 9 cases. Even with only 4 gallons of water, the zoned system was effective, increasing the available escape time by 53 seconds. The optimal nozzle discharge rate was 0.35 gpm.

In order to optimize the water quantity, the efficiency of a water spray system was defined as the ratio of the additional available escape time (seconds) to the quantity of water discharged (gallons), or seconds per gallons (SPG). Figure 7 compares SPG for the various water spray configurations on the basis of nozzle flow rate. It is evident that the most efficient or optimum zoned system utilized a medium flow rate nozzle (0.35 gpm) and a water quantity of 8 gallons. The optimum zoned water spray system (SPG = 20.4) was a factor of 13.6 more efficient than the continuous waters spray system (SPG = 1.5). It is significant that as much as 20 seconds of additional available escape time per gallon of water discharged may be achieved by a water spray system, operating effectively in a postcrash fire environment, where each second of available escape time is critical.

Improved visibility is another advantage of a zoned water spray system since continuously discharging water throughout the airplane tends to lower the ceiling smoke layer. With the zoned system the disruption of the smoke layer is primarily confined to the spray zones. Visibility during the zoned system tests improved by approximately 40-50 seconds compared to the SAVE system test (figure 8).

5. EFFECTIVENESS OF ZONED CABIN WATER SPRAY SYSTEM

Wide-Body Test Article. The effectiveness of a zoned water spray system was examined in the wide-body test article. The placement of nozzles was similar to the narrow-body arrangement with two exceptions. First, there were six nozzles in each of the two boundary planes. Second, for some tests a half-zoned geometry was used; i.e., the zone extended to the cabin symmetry plane rather than across the full cabin width. Another variation in some tests was the spray discharge activation temperature. As in the narrow-body tests, initial activation of spray discharge was set at 300 degrees F; however, subsequent zone activation's were delayed until the temperature reached 500 degrees F. This was done with the aim of conserving water for application in the initial zone where the fire intensity was greatest. The total quantity of water was only 21

gallons (vs. 195 gallons with the SAVE system). This was calculated by scaling to the optimum zone system and SAVE system water quantities in the narrow-body test article.

The calculated FED profiles are shown in figure 9. As in the narrow-body test article, the zoned water spray configurations provided a significant increase in survival time, ranging form 86 to 103 seconds under the conditions tested. Again, the medium flow rate nozzle (0.35 gpm) was more effective than the high flow rate nozzle (0.50 gpm), although by a relatively small amount (10 seconds). Small improvements are also seen from split zoning and elevation of discharge activation temperature in secondary zones (7 seconds).

Commuter Test Article. Currently, small commuter aircraft (19 seats or less) are exempt from the stringent FAA regulations that require seat cushion fire blocking layers and low heat/smoke release panels in large transport aircraft. To determine potential improvements in postcrash fire survivability from usage of more fire resistant materials in commuter aircraft, and from a zoned water spray system, a series of full-scale tests were conducted in a Metroliner fuselage.

The fire scenario setup for the commuter test article was similar to that used in the large transport test articles, except on a reduced scale; e.g., 4-by-5-foot pan fire adjacent to 20-by-26-inch initial fuselage opening. The water spray system was comprised of 100 inch long zones, with each zone containing six nozzles. Only 5 gallons of water was discharged.

Figure 10 presents the survival time improvements resulting from fire blocked seats, improved panels and a water spray system. Each fire safety design improvement created finite survival gains. By far the largest increase in survival time was furnished by the water spray system - over 3 minutes. It was also shown in other tests that this incremental improvement would also be attained with less fire resistant materials. It is interesting that the survival time improvement for seat fire blocking layers, 45 seconds, is within the range measured previously in large transport full-scale fire tests (Sarkos, 1989).

6. EVALUATION OF CARGO COMPARTMENT WATER SPRAYS

An in-flight cargo fire presents a totally different fire threat than a postcrash cabin fire. The latter is an intense, open fire which must be suppressed for several minutes in order to enable passengers to escape. A cargo fire, however, may be a deep-seated fire, potentially involving a wide variety of cargo and baggage materials, which must be suppressed and contained within the confines of the cargo compartment. The period of protection must allow the airplane to be safely landed, which in some cases may be as long as 180 minutes.

The cargo compartment water spray tests conducted to date represent a worst case scenario. Since it is expected that water spray will effectively extinguish or suppress a fire originating in bulk-loaded cargo, testing has focused on water spray protection against fires in cargo containers. The test arrangement is shown in figure 11. It would appear that a containerized cargo fire presents greater discharge obstructions and less opportunity for soaking of cargo materials than a bulk-loaded cargo fire (individually loaded luggage and/or cargo). A standard fire load, consisting of cardboard boxes filled with shredded paper at a packing density of 2.5 pounds per cubic foot, was employed in all the tests. An unsuppressed fire burns out of the container through the polycarbonate walls. Aircraft Halon 1301 systems are designed to maintain an inerting concentration of Halon 1301 (>3%) throughout the period of protection, in effect, suppressing a deep-seated fire by preventing the occurrence of open flaming.

Two types of nozzles were evaluated in a zoned water spray configuration - high pressure and dual fluid. The high pressure nozzle produced a water fog at a flow rate of .027 liters/minute; the dual fluid nozzle discharged water mist at 2.5 liters/minute. Since water did not remain suspended in air for any appreciable time with either system, it was necessary to control the discharge of water based on temperature measurements taken within each zone.

The dual fluid nozzle water spray system was evaluated initially. A series of eight tests were conducted, varying the discharge activation temperature (200-300°F), deactivation temperature (150-290°F), and/or spray duration (6-10 seconds). The dual fluid nozzle system was effective in controlling the cargo fire, but the required quantity of water was excessive, ranging from 80 to 110 gallons, and showed little sensitivity to the parameters studied.

The initial tests with a high pressure spray system exhibited some reduction in the required quantity of water (minimum of 65 gallons). However, in order to be a candidate replacement for a Halon 1301 system, the water usage should be in the 10 to 20 gallon range. Therefore, the nozzle arrangement was modified by incorporating nozzles which sprayed directly downward in the space between the containers, in addition to the previous arrangement of nozzles which sprayed horizontally at the ceiling. Figure 12 shows this nozzle arrangement. Also shown is the cargo container fire configuration employed throughout the test program. As shown in Figure 12, the fire origin was in the lower corner container (the adjacent "blank" containers provided discharge obstructions). There were a total of eight spray zones, although only the single zone in which the fire was started activated in all of the tests. The fire zone discharged water at a rate of 1.0 gallon per minute (minimum flow rate required to suppress the fire).

A typical water spray test with the high pressure system is shown in figure 13. A 200°F activation temperature, 20 second spray duration and 10 second scan rate was employed during the test. The ceiling temperature measured above the cargo container was well below the safe level. Also, the oxygen concentration profile demonstrates that the fire was controlled by water spray (versus oxygen starvation). The quantity of water used, 41.3 gallons, demonstrated that the downward spraying nozzles significantly reduced water usage (65 gallons was the minimum quantity when only horizontal spray nozzles were employed). Moreover, in subsequent cargo container fire tests, by modifying certain spray parameters, the fire was controlled for 90 minutes by utilizing only 31.0, 34.4 and 31.6 gallons of water.

In order to evaluate the effectiveness of the spray system during a simulated bulk loaded cargo fire, 56 shredded paper filled boxes were arranged in two tiers of 7 boxes. A second water spray zone with a high concentration of downward spraying nozzles was added because the floor area of the bulk loaded cargo occupied two zones. The flowrate in each of these zones remained at 1.0 gallons per minute (identical to the container test which needed the least amount of water). During the first test, the spray was activated when the ceiling temperature reached 250°F, which allowed temperature excursions within the compartment to reach unacceptable levels (300°F to 800°F). Because the high activation temperature allowed the fire to grow sizably before allowing the system to gain control, an excessive 42 gallons of water was used. The next test used a 150°F activation temperature, which produced noticeably superior results in terms of both the temperatures observed and the amount of water required (24.8 gallons).

7. SUMMARY OF RESULTS

Full-scale tests demonstrated that an on-board cabin water spray system provided significant increases in survival time in all transport aircraft sizes during a postcrash fire. The main benefits of water spray were to delay the onset of flashover, reduce cabin air temperatures, and remove water-soluble toxic gases. Moreover, a zoned water spray system, utilizing relatively small quantities of water, increased the survival time and improved visibility when compared to a system that continuously discharged water throughout the cabin. Enhancement in survivability by zoning was attributed to concentrating the discharge of water to those cabin areas where the fire originated and spread, and to reducing the lowering of the smoke layer caused by water discharge. Full-scale tests also demonstrated that a cargo compartment zoned water spray system, employing either dual fluid or high pressure nozzles, effectively controlled a deep-seated in-flight fire, originating inside a cargo container, for a period of 90 minutes. Significant reduction in water quantities were attained by altering the nozzle arrangement and optimizing certain discharge parameters, such as zone spray activation temperature.

8. THE FUTURE OF AIRCRAFT WATER SPRAY SYSTEMS

The full-scale cabin fire tests described in this paper was part of a broad multi-national program, conducted primarily by FAA and CAA, to determine the feasibility and practicality of an onboard cabin water spray system for enhanced postcrash fire survivability. Various tests and studies were conducted to address the following issues: system effectiveness, system optimization, physiological hazards and other human factors, safety benefit analysis, manufacturer's disbenefits studies, airworthiness requirements and cost analysis (CAA, 1993). It was essentially determined that a zoned cabin water spray system is effective, safe and practical (some protective measures may be needed to tolerate an inadvertent discharge). These findings led to consideration of the of the development and evaluation of a prototype water spray system in an operational aircraft. Further development of a cabin water spray system, however, was discontinued after a cost/benefit analysis determined the high costs associated with life saving potential, approximately \$20-30 million per life saved (CAA, 1993).

An aircraft cabin water spray system may still be a viable concept. Although the average benefit based on an analysis of past accidents and factoring in the impact of regulatory fire safety improvements is relatively small, there is the potential for alleviating a major loss of life in a single accident. The potential benefit may be even more pronounced in future, high capacity double-decked transports. Most important, however, is the potential significant reduction in cabin system cost if water spray were also incorporated as a halon alternative fire suppression agent in cargo compartments. It is conceivable that the quantity of water required to suppress a cargo compartment fire will also provide adequate capacity to supply a zoned, cabin water spray system. Utilization of potable water offers added protection and cost reduction depending on the fire scenario, flight type (over land vs. over water), etc.

Initially, aircraft manufacturers and airlines generally favored a gaseous halon replacement agent in cargo compartments, primarily because gases are "clean" and would require virtually no cleanup in the event of an accidental discharge. However, currently available halon replacement gaseous agents have one or more of the following disadvantages: additional weight and volume, greater toxicity, unknown future environmental restrictions, and higher cost. Obviously, toxicity, environmental concerns and cost (agent) are not concerns with water. Freezing is an issue that needs to be addressed. Further reduction in the quantity of water required to suppress a cargo fire may be possible because of the many options offered by zoned water spray. Water spray in aircraft cargo compartment fire

suppression systems is a halon replacement option that exhibits more promise than envisioned several years ago.

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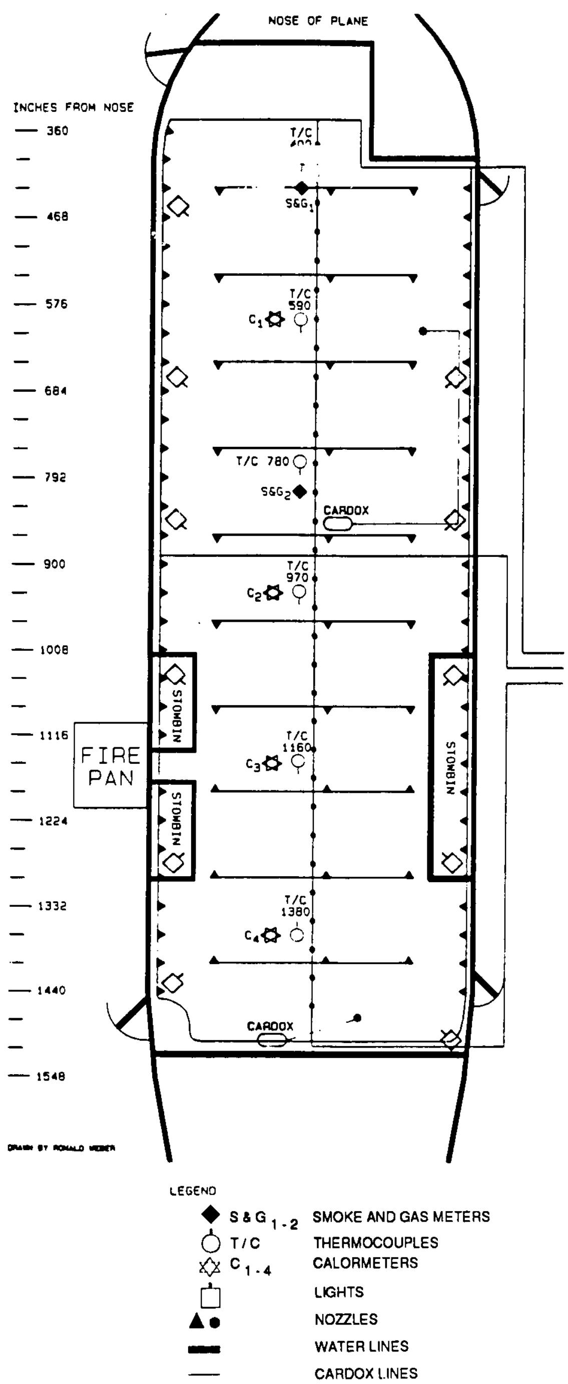

FIGURE 1. NARROW CABIN BODY TEST SETUP, SAVE SYSTEM

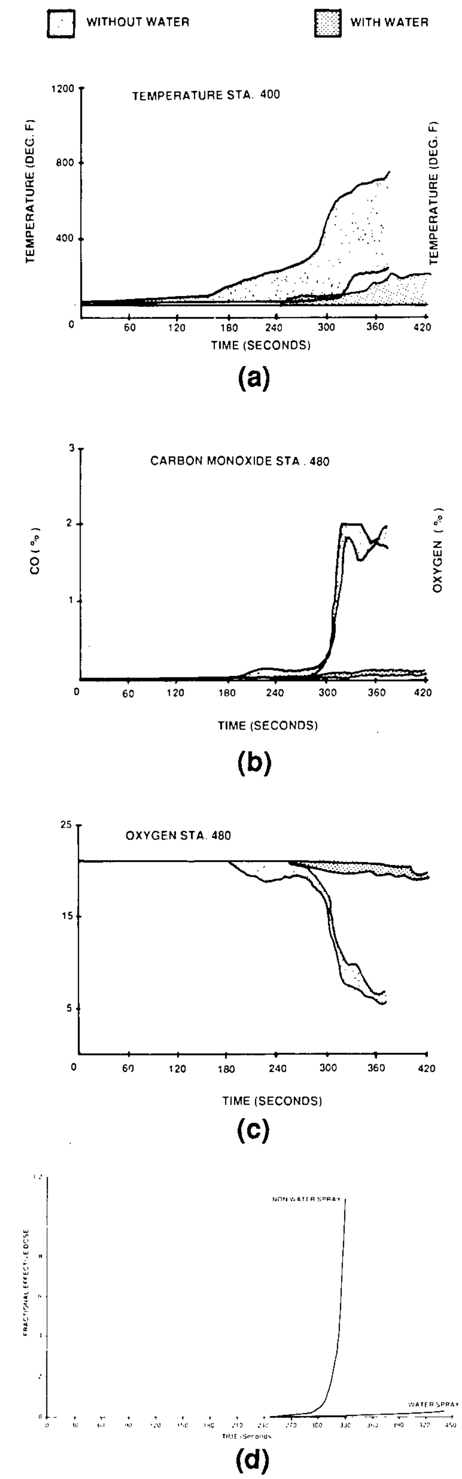

FIGURE 2. NARROW CABIN BODY RESULTS/SAVE SYSTEM/ZERO WIND

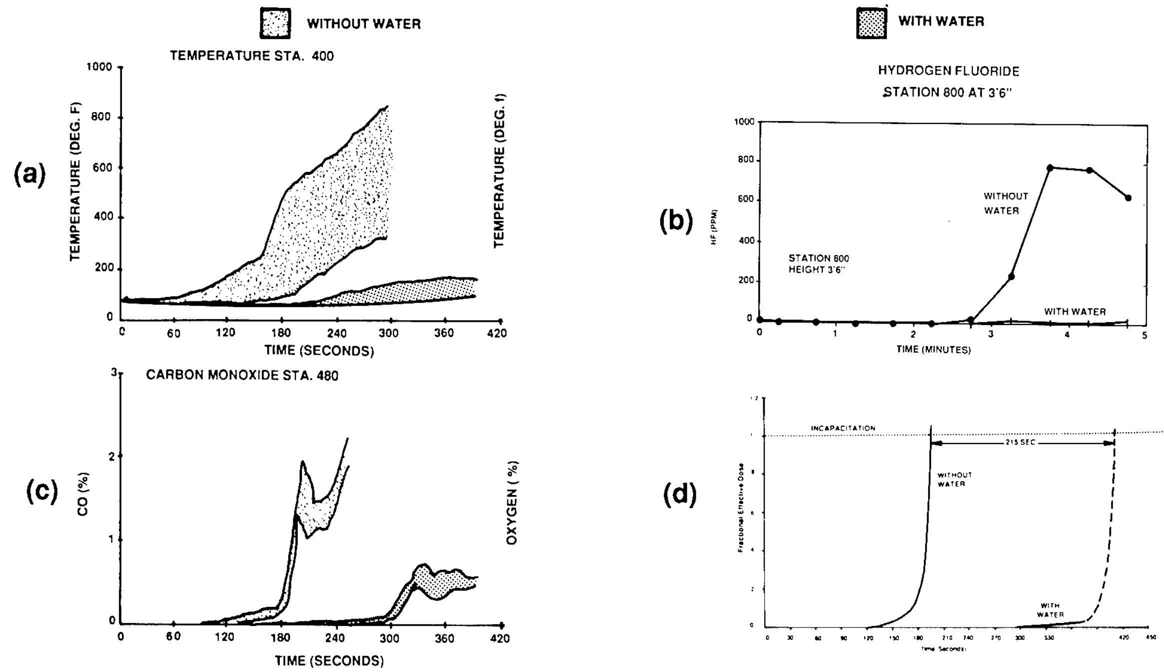

FIGURE 3. NARROW CABIN BODY RESULTS/SAVE SYSTEM/MODERATE WIND

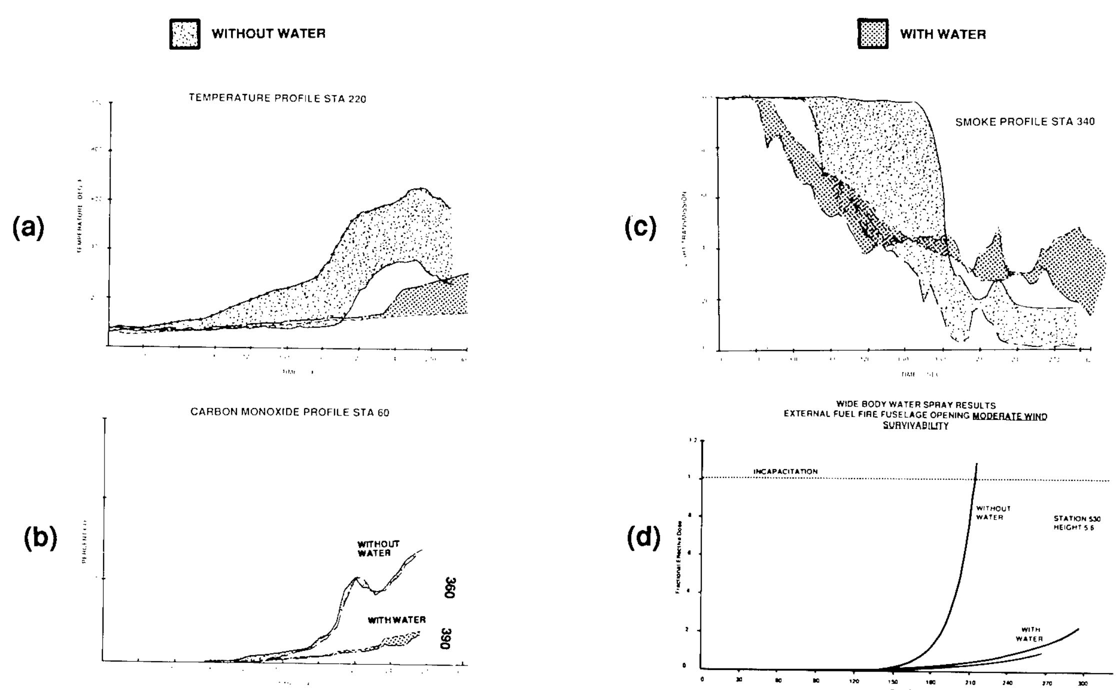

FIGURE 4. WIDE CABIN BODY RESULTS/SAVE SYSTEM/MODERATE WIND

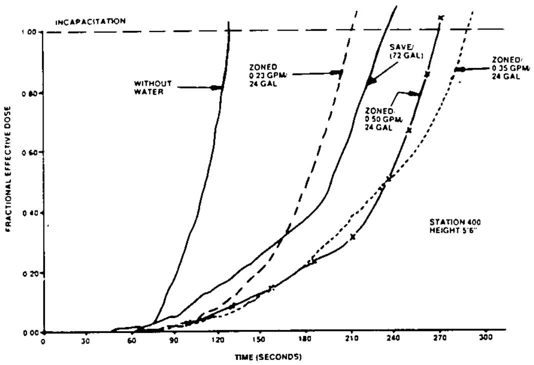

FIGURE 5. CABIN ZONED SYSTEM SURVIVAL TIME IMPROVEMENT, 24 GALLONS

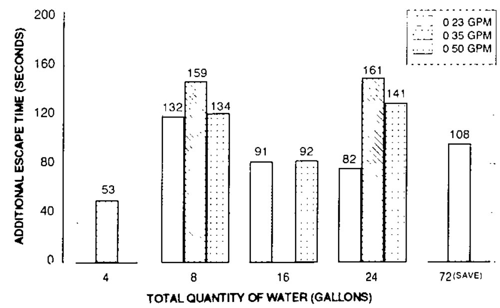

FIGURE 6. CABIN ZONED WATER SPRAY TEST RESULTS ADDITIONAL ESCAPE TIME

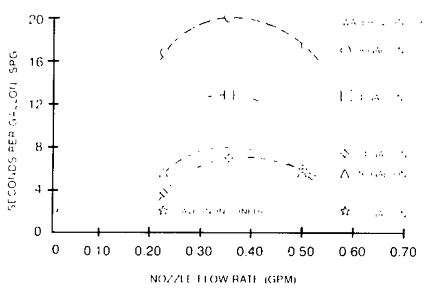

FIGURE 7. CABIN ZONED WATER SPRAY OPTIMIZATION TEST RESULTS

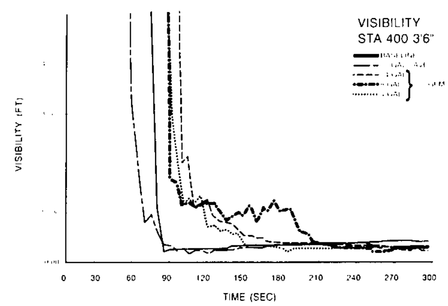

FIGURE 8. CABIN ZONED SYSTEM VISIBILITY IMPROVEMENT

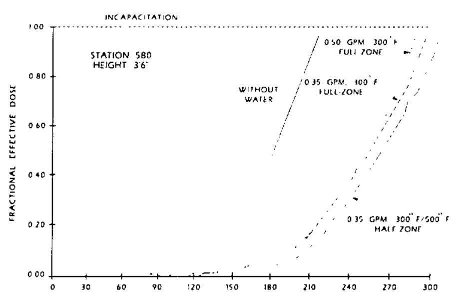

FIGURE 9. WIDE-BODY CABIN ZONED SYSTEM SURVIVAL TIME IMPROVEMENT

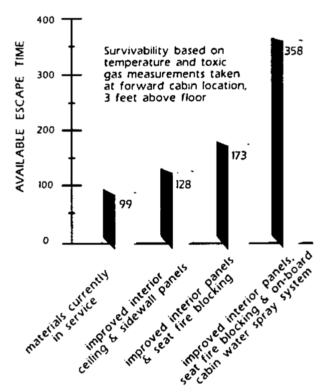

FIGURE 10. SURVIVABILITY IMPROVEMENTS IN COMMUTER TEST ARTICLE

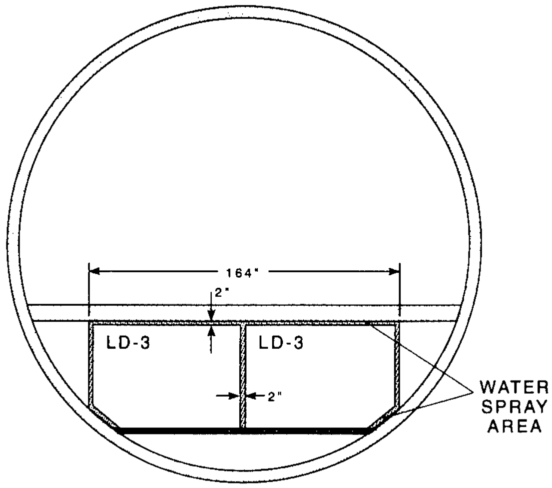

FIGURE 11. DC-10 CARGO COMPARTMENT CROSS SECTION

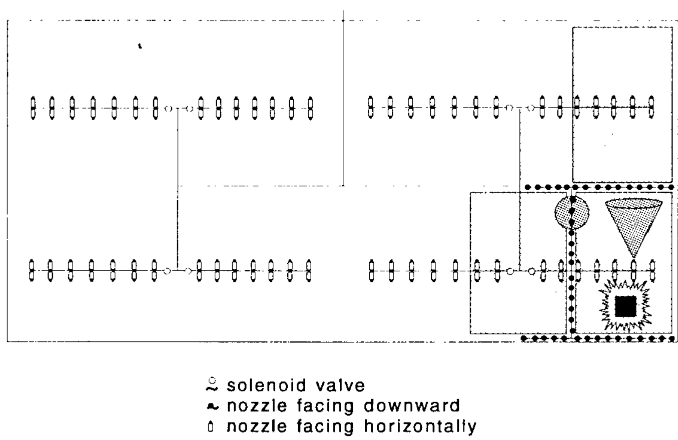

FIGURE 12. CARGO COMPARTMENT HIGH PRESSURE SPRAY SYSTEM

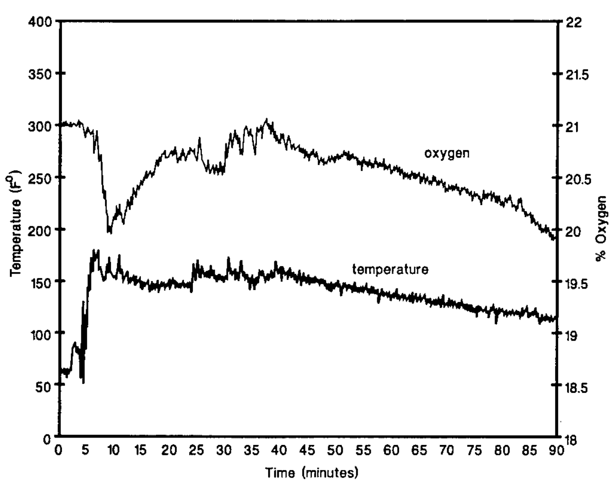

FIGURE 13. HIGH PRESSURE CARGO COMPARTMENT SYSTEM
OXYGEN AND TEMPERATURE PROFILES

DISCUSSION - PAPER NO. 12

A. Mulder (Comment & Questions)

Comment: Very worthwhile research.

Questions:

1) Is there any knowledge about the difference in hazards between inhaling smoke, and smoke mixed with water mist?

2) With respect to Water Spray Systems in cargo compartment, are the so-called 'shaded areas' not a problem?

C.P. Sarkos - Author (Response)

1) What is most important is a comparison of the hazards at a given location and point in time with water spray and without water spray. Measurements during full-scale fire tests with water spray show significantly lower temperatures and toxic gas concentrations than without water spray. Also, the occurrence of flashover is delayed significantly. Similarly, in tests sponsored by the CAA, the collection of particles of various sizes that could be ingested showed lower levels of harmful deposits when water spray was used.

2) FAA cargo compartment fire tests have focused on the 'shaded area' created by a cargo container fire. Until the fire burns out of the container, any water spray discharge will be shielded from the fire. By using a ceiling temperature sensor, the fire could be controlled for 90 minutes by discharging water for 20 seconds if the temperature exceeded 200°F (10-second interrogation time).

N.J. Povey (Comment)

Additional comment to previous questions and answers. The CAA, as part of the joint FAA/CAA/TCCA programme - conducted a study (performed by Dr. David Purser - to investigate the risk posed by respirable water droplets (reported in CAA Paper 93009). Conclusion was that there was no additional risk. The benefit of water in stopping the production of toxic gases far exceeded any additional risk of respirable droplets.

H. Schmidt (Question)

Did you investigate the influence of droplet size or droplet size distribution to extinguishing efficiency?

C.P. Sarkos - Author (Response)

We did not investigate the variation of droplet size to determine its effect on extinguishment efficiency. The cabin water spray system employed a mean droplet diameter of about 100μ. One concern for the cabin system was not to employ droplet sizes in the 20-30μ range which might be respirable. Smaller droplet sizes were used in the cargo system with the hope that a total flooding behaviour would result and the droplets would remain suspended for long periods of time.

W.B. de Wolf (Question)

1) Could you comment on the cost/benefit aspect of water spray systems based on the present technical status?

2) Could you also comment on possible patent issues?

R.G. Hill - Author (Response)

1) Cabin water mist systems have not been shown to be cost beneficial at present. However, if a cargo water mist system is shown to be acceptable as a Halon replacement, the cost of additional cabin protection may become cost beneficial.

2) Although some components specific to water mist systems may be patented, the concept is not.

Synthesis and Properties of Various Alternative Fire Extinguishing Agents

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The two bromine based fire extinguishing agents, HALON 1211 (CF_2ClBr) and Halon 1301(CF_3Br), are extremely effective at extinguishing major conflagrations. Particularily they offer a reliable way of combating fuel, solvent and gas fires.

However, these agents are also characterised by a high Ozone Depletion Potential (ODP) and this is the reason why their production has been almost entirely phased out in those countries that have ratified the Montreal Protocol.

In the following compilation the data of the history of HALONEs are given.

1. History of HALONs

1881:
A chemist in Antwerp discovers the fire extinguishing capabilities of Chloroform

from 1900:
Carbon tetrachloride is recommended as fire extinguisher

from 1926:
Dichloroethane, Trichloroethane, Perchloroethylen and Pentachloroethane are used as fire extinguishing agents

1933:
C. Duffraisse observed that bromo and iodo hydro carbons exhibit a better fire extinguishing capability than their chloro counterparts

1939:
Development and market introduction of chloro-bromo-methane (CB) as a fire extinguishing agent

from 1960:
Development of bromine containing fluoro-(chloro)-carbons

from 1966:
Market introduction of the most important HALONEs: 1301 = CF_3Br, 1211 = CF_2ClBr, 2202 = CFClBr-CFClBr, 2402 = CF_2Br-CF_2Br

1987:
Signing of the Montreal Protocol on the protection of the earth atmosphere / start of the phase out of the HALONEs and CFC's

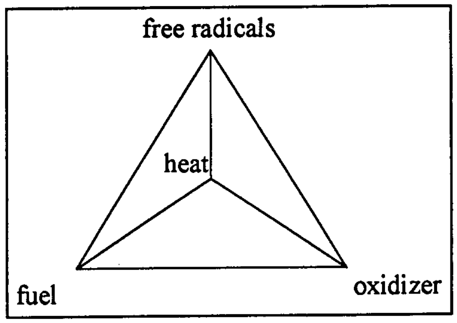
1994: HALONEs are banned by the latest revision of the Montreal Protocol.

2. Fire extinguishing

The activity of the fire extinguishing agents on the processes during the conflagration is very complex:
For the process of combustion four conditions must be fulfilled:

- the presence of fuel
- heat
- presence of an oxidiser
- free radicals

Starting from these requirements the so called 'fire tetrahedron' can be postulated



Elimination or inhibition of one of these four components within the 'fire tetrahedron' stops the molecular processes of combustion and the fire can be extinguished.

For an effective fire fighting organic molecules, like the HALONEs, can be used. They exhibit their effects on the fire by various mechanisms:

Mechanism	Effect
- Physical	
Dilution	Reduction of the concentration of reactive species
Vaporisation	Absorption of flame energy, reduction of temperature
Heat-transfer	Absorption of flame energy
Dissociation	Absorption of flame energy
- Chemical	
Reaction	Elimination of reactive species within the flame

The following example illustrates the working mechanism of HALONE 1301 in a simplified form.

Reaction mechanism of the fire extinguishing agents HALONE 1301

Formula	ΔH (kJ at 298K)
1. $CF_3Br + H\bullet \Rightarrow CF_3\bullet + HBr$	+76
2. $H\bullet + HBr \Rightarrow H_2 + Br\bullet$	-70
3. $Br\bullet + RH \Rightarrow HBr + R\bullet$	+46
4. $H\bullet + H\bullet \Rightarrow H_2$	-436
5. $H\bullet + O_2 \Rightarrow HO\bullet + O$	+70
6. $H_2 + O\bullet \Rightarrow HO\bullet + H$	+8
7. $Br\bullet + Br\bullet + M \Rightarrow Br_2 + M^*$	-224
8. $H\bullet + Br_2 \Rightarrow HBr + Br\bullet$	-143
9. $R\bullet + Br_2 \Rightarrow RBr + Br\bullet$	-69
10. $CF_3Br + Br\bullet \Rightarrow CF_3\bullet + Br_2$	-67
11. $H\bullet + CF3\bullet + M \Rightarrow HCF_3 + M^*$	-445
12. $HO\bullet + CF_3Br \Rightarrow CF_2O + HF + Br\bullet$	-339
13. $CF_3Br + O\bullet \Rightarrow CF_3\bullet + \bullet OBr$	+56
14. $HO\bullet + CF_3Br \Rightarrow CF_3\bullet + HOBr$	+60

This reaction scheme can be interpreted as follows:

Equation 1: First step: Bromine is abstracted from the organic molecule.

Eq. 1-3: These reactions interfer with the key chain branching reaction, in which hydrogen reacts with oxygen (4 + 5). Bromine catalyses the recombination of the hydrogen atoms whereby each bromine atom is used over and over owing to the recycling reaction in formula 7.

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

Eq. 13-14: CF_3Br can react directly with oxygen containing radicals. The efficacy of halogenated fire suppressants increases, as mentioned above, with the atomic weight of the halogenes (F< Cl<Br<I). The molar heat capacity increases also with the molecular weight of the fire suppressants. This results in an increasing impact on the physical fire suppressing effects. One effect reinforces the other, that means boosting the efficacy of the fire extinguishing agent.

3. Replacement of HALONEs

Beside the capability of extinguishing the fire by forming radicals interfering with the radical chain mechanism the following properties are required:

- low ODP
- low GWP
- low toxicity (acute and chronic)
- high purity
- high effectivity
- no conductivity
- no corrosivity
- cost effectivity
- decrease athmospheric lifetime

Like in the case of the old HALONEs various types of alternative fire extinguishing agents are necessary:

- total flooding agents
- streaming agents
- specialised agents (explosion suppression, inertion)

The worldwide efforts to develop new fire extinguishing agents have yielded in an extensive investigation in the fluoro carbons. The most promissing compounds can be found among the listed substance classes:

Perfluoralkanes	FCs
Hydrofluorocarbons	HFCs
Hydrochlorofluorocarbons	HCFCs
Hydrobromofluorocarbons	HBFCs
Fluoroiodocarbons	FICs

As replacements the following compounds are in discussion:

Table 1: Compounds under discussion as fire extinguishing agents

Agent	Chemical	Formula
Halons		
1301	*Bromotrifluoromethane*	*CF_3Br*
1211	*Bromochlorodifluoromethane*	*$CBrClF_2$*
Perfluorocarbons		
FC 116	Perfluoroethane	CF_3-CF_3
FC 218	Perfluoropropane	CF_3-CF_2-CF_3
FC 3-1-10	Perfluorobutane	CF_3-CF_2-CF_2-CF_3
FC 5-1-14	Perfluorohexane	CF_3-CF_2-CF_2-CF_2-CF_2-CF_3
Hydrofluorocarbons		
HFC 23	Trifluoromethane	CHF_3
HFC 125	Pentafluoroethane	CHF_2-CF_3
HFC 134a	1,1,1,2-Tetrafluoroethane	CH_2F-CF_3
HFC 227ea	1,1,1,2,3,3,3-Heptafluoropropane	CF_3-CHF-CF_3
HFC 236fa	1,1,1,3,3,3-Hexafluoropropane	CF_3-CH_2-CF_3
Hydrochlorofluorocarbons		
HCFC 123	2,2-Dichloro-1,1,1-trifluoroethane	$CHCl_2$- CF_3
HCFC 124	2-Chloro-1,1,1,2-tetrafuoroethane	CHClF- CF_3
Blends		
Blend A		
HCFC 123	2,2-Dichloro-1,1,1-tetrafluoroethane	$CHCl_2$- CF_3
HCFC 22	Chlorodifluoromethane	$CHClF_2$
HCFC 124	2- Chloro-1,1,1,2 tetrafluoroethane	CHClF- CF_3
Blend B		
HCFC 123	2,2-Dichloro-1,1,1-trifluoroethane	$CHCl_2$-CF_3 primarily
Blend C		
HCFC 123	2,2-Dichloro-1,1,1-tetrafluoroethane	$CHCl_2$-CF_3
HCFC 124	2-Chloro-1,1,1,2-tetrafuoroethane	CHClF- CF_3
HFC 134a	1,1,1,2-Tetrafluoroethane	CH_2F-CF_3
Fluoroiodocarbons		
FIC 1311	Trifluoroiodomethane	CF_3I
Inert Gas Alternatives		
IG 541	52% Nitrogen, 40% Argon, 8% CO2	
IG 55	50% Nitrogen, 50% Argon	
IG 01	100% Argon	
IG 1	100% Nitrogen	

The synthesis of these compounds is performed by many different routes depending on the raw materials and the technology used. This is reflected by the costs of the procedure of the production.

The following examples show simplified synthetic routes for the different classes of fire extinguishing agents:

1. *Bromofluorocarbon*
   HALON 1301:

   $CHCl_3 + 3HF \Rightarrow cat \Rightarrow CF_3H + 3HCl$
   $CF_3H + Br_2 \Rightarrow cat \Rightarrow CF_3Br + HBr$
   catalytic liquid or gasphase reaction

2. Perfluorcarbons
   FC 116

   $CCl_2{=}CCl_2 + Cl_2 + 6HF \Rightarrow CF_3\text{-}CF_3 + 6HCl$
   catalytic gasphase reaction

3. Hydrofluorcarbon
   HFC125:

   $CCl_2{=}CCl_2 + 5HF \Rightarrow CF_3\text{-}CHF_2 + 4\,HCl$
   catalytic liquid and / or gasphase reaction

4. Hydrochlorofluorocarbons
   HCFC124:

   $CCl_2{=}CCl_2 + 4\,HF \Rightarrow CF_3\text{-}CHFCl + 3\,HCl$
   catalytic liquid and / or gasphase reaction

5. Iodofluorocarbons
   FIC1311

   $CF_3Br + Zn + I_2 \Rightarrow CF_3I + ZnIBr$
   Grignard Reaction

International research programs on the properies, the efficiency of the fire suppresion and the enviromental aspects have been performed like:

- development of an experimental database on the inhibiting properties
- mechanism, determination and modelling
- analysis of the potential athmospheric impact

Some of these data are given in the enclose tables:
Table 2 shows the performance data.
Table 3 shows the environmental characteristics like ODP, GWP, atmospheric lifetime and toxicity.

4. Conclusions

The effects of fire extinguishing agents are described by various research reports.

The following conditions for an effective conflagration fighting must be fulfilled:

1. Inhibition of oxidation reactions:
Applying isothermal conditions the inhibition effect is caused by bromine. FCs, HFCs and HCFCs do **not** inhibit oxidation reactions, for example of CH_4. Isothermal conditions are: 700°C, attempt to ignite combustion, check for suppression properties

2. Flame inhibition:
The effectivity of the flame inhibition correlates with the number of fluorine atoms in the molecule

$CF_3Br > C_3F8 > C_3F7H > C_2F6 > C_2ClF4H > C_2F_4$

3. Detonation inhibition:
Halogenated compounds in sufficient concentrations can inhibit detonations.
$CF_3Br > CF_2BrH < CFCl_3 > CF_2Cl2 > CF_3Cl > CF_2ClH > CF_3C\ CLFH > C_3F_8 > C_2F_5H > C_2F_4H_2 > CF_3H; CF_4$

4. Reaction mechanism:
The inhibition by brominated compounds depends on the bromine cycle. For FCs, HFCs and HCFCs the reaction mechanism is not yet fully elucidated.
Physical influence: heat adsorption
Chemical influence: formation of CF• radicals

5. Proposal:
Considering all important properties mentioned above the best candidates as an alternative for the old HALONEs seem to be among the CFs, HFCs and the HCFCs:

227ea and 125

CF_3I in its reaction mechanism and efficiency is comparable with CF_3Br and has a special rank among the alternative fire extinguishing agents.

Table 2: Perfomance Data of Alternative Fire Extinguishing Agents

Agent		Molecular weight	Extinguishment concentration Vol%	Liquid Density g / ml	Weight Equivalent	Storage Volume Equivalent	TFR	SR
Halon	*1301*	*148,93*	*2,9*	*1,54*	*1,0*	*1,0*	+	
	1211	*165,40*	*3,8*	*1,83*	*1,45*	*1,22**		+
FC	116	138,01	7,8	1,607 / 78°C	2,49	1,99		
	218	188,02	6,11	1,35	2,66	3,03	+	
	3-1-10	238,03	5,49	1,52	3,03	3,06	+	
	5-1-14	338,03	4,40	1,73	3,44	3,07	+	+
HFC	23	70,01	12,6	1,20	2,04	2,62	+	
	125	120,02	9,4	1,189	2,61	3,39	+	
	134a	102,03	10.5	1,21	2,48	3,16		
	227ea	170,03	6,3	1,39	2,48	2,75	+	+
	236fa	152,04	5,6	1,37	1,97	2,22	+	+
HFC	123	152,94	7,1	1,466	2,2	2,3		+
	124	136,48	6,7	1,364	2,12	2,39	+	+
	Blend A	92,0	9,9	1,20	2,13	2,73	+	
	B							+
	C							+
FIC	1311	195,91	3,02	2,096	1,37	1,01	+	
IE	541							
	55							
	01							
	1							

TFR: Total Flood Replacement
SR: Streaming Replacement

Table 3: Enviromental Characteristics of the Alterantive Fire Extinguishing Agents

Agent		ODP	GWP	Atm. Lifetime Yrs	NOAEL %	LOAEL %
HALON	*1301*	*12-13*	*5 600*	*65*	*5*	*7,5*
	1211	*3*		*15*	*0,5*	*1,0*
FC	116	0,0	12 500	10 000		
	218	0,0	6 100	3 200	30	40
	3-1-10	0,0	5 500	2 600	40	>40
	5-1-14	0,0	6 800	3 200	400	>40
HFC	23	0,0	12 100	250	30	>50
	125	0,0	3 200	36	7,5	100
	134a	0,0	1 300	15	4,0	8,0
	227ea	0,0	3 300	41	9,0	10,5
	236fa	0,0	8 000	250	10,0	15,0
HCFC	123	0,02	93	1,4	1,0	2,0
	124	0,022	480	6	1,0	2,5
	Blend A	0,044	1450	12	10,0	>10,0
	Blend B	0,02	93	1,4	1,0	2,0
	Blend C					
FIC	1311	0,0001	<5	> 1 day	0,2	0,4
IG	514	0,0	-	-	-	-
	55	0,0	-	-	-	-
	01	0,0	-	-	-	-
	1	0,0	-	-	-	-

NOAEL: **No Observed Averse Effect Level** (Cardiotoxicity)
LOAEL: **Lowest Observed Adverse Effect Level** (Cardiotoxocity)

The data in *italics* of HALONEs are given for comparative purposes.

Extinguishing of Aircraft Interior Fires with Halon Replacements for Handheld Extinguishers

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1. SUMMARY

Because the halons have to be abandoned in the near future the effectiveness of possible replacements for attacking initial fires in civil aircrafts must be investigated. This lecture reports on fire extinguishing experiments with handheld extinguishers on aircraft carpet and seats. Three so-called halon alternatives were compared to the Halon 1211, which is still in use in aviation. To set the aircraft interior on fire for experimental purposes, gasoline was used as fire accelerator which is thought to be realistic in a terroristic attack versus an aircraft. Furthermore, a small-scale hidden fire mock-up is presented. Employing this mock-up the extinguishing qualities of new extinguishing agents can be estimated by laboratory means.

2. NOMENCLATURE

Symbol	Unit	Meaning
GWP	[-]	Global Warming Potential
LOAEL	[%]	Lowest Observed Adverse Effect Level
m	[g]	Mass
MAK	[ppm]	Maximum Allowed Concentration at Working Place
NOAEL	[%]	No Observed Adverse Effect Level
ODP	[-]	Ozone Depletion Potential
ppm		Parts per million
t	[s]	Time
vol.%		Volume percentage
σ		Standard deviation

3. INTRODUCTION

For more than 30 years the halons were used successfully for fire fighting. They represent an optimal compromise between extinguishing efficiency, toxicity, mass, availability and price.

Halons are partly or completely halogenized hydrocarbons. They belong to the hydrochlorided fluorocarbons (HCFCs) which have been banned by the western world in the Montreal Protocol because of their ozone depleting properties. Since January 1994 the use and production of halons is not allowed anymore. An exception exists for aviation besides some other fields for the further use because of the importance of an optimal extinguishing agent on the one hand and the lack of an acceptable alternative on the other. This exception expires with the year 1999 (in Germany 1998). To the airlines' and airframe manufacturers' mind there is the most urgent need for a halon replacement in the sphere of handheld extinguishers.

Chemical industry, aviation research establishments and officials work together to develop an alternative for Halon 1211 (Difluorochlorobromomethane CF_2ClBr), which is used in handheld extinguishers and for Halon 1301 (Trifluorobromomethane CF_3Br), for the extinguishing systems of aircraft cargo compartments and engines. The demand is that a real halon alternative is at any field at least as good as the halons (one-to-one replacement).

4. EXAMINED AGENTS AND THEIR ENVIRONMENTAL PROPERTIES

During the later described tests the following halon alternatives were compared with Halon 1211 concerning extinguishing efficiency and toxicity:

1) Triodide (Trifluoroiodomethane CF_3J), a Pacific Scientific extinguishing agent. It is a completely halogenized methane, its molecular structure is similar to the Halon 1301. Instead of bromine (Br) its molecule contains the more reactive iodine (J). Its ozone depletion potential ODP, which are the calculated ozone depletions per mass unit referred to a standard agent which normally is the refrigerant R 11 (CFC 11, $CFCl_3$), is nearly zero because of the very short atmospheric lifetime of less than 1 day. Therefore also its global warming potential, which is the change in radiative forcing of 1 kg emitted agent referred to 1 kg standard agent, usually carbondioxide (CO_2), is very little. The NOAEL and LOAEL values are very small. NOAEL and LOAEL are determined by dog tests and indicate the breathed-in concentration with no adverse effect or respectively the lowest concentration where an adverse effect, here the cardiac sensitization, occurs. So, high NOAEL and LOAEL mean low toxicity and the higher the NOAEL/LOAEL are above the necessary extinguishing concentration inside a room the better for the fire worker or a possible victim inside that room. The agent's boiling point is at -22.5°C.

2) FM 200 (Fire Master 200, Heptafluoropropane C_3F_7H),

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

a Great Lakes extinguishing agent. It is a partly halogenized propane. Besides fluorine (F) its molecule contains no further halogens and it has no ozone depleting properties. Because of its relatively long atmospheric lifetime it has a mediocre global warming potential. Also its NOAEL and LOAEL values are in the middle range. The agent's boiling point is at -17°C.

3) CEA 614 (Clean Extinguishing Agent 614, Tetradecafluorohexane C_6F_{14}), a 3M extinguishing agent. It is a completely halogenized hexane. It has no ODP but because of its very long atmospheric lifetime a high GWP. The NOAEL is very high, a LOAEL is not known. CEA 614's boiling point is at 56°C. It is the only agent which is liquid at room temperature.

The physical and environmental qualities of the agents are listed in Fig. 1 (/1/-/9/).

AGENT / PROPERTY	HALON 1211	TRIODIDE	FM 200	CEA 614
CHEM. FORMULA	CF2ClBr	CF3I	C3F7H	C6F14
ODP 1)	3	0,0001	0	0
GWP 2)	(-) 5)	<5	2050	5200
ATMOSPH. LIFETIME [years]	15	<1day	31	3100
NOAEL [%]	0,5	0,2	9	18
LOAEL [%]	1	0,4	10,5	(-) 5)
DENSITY [kg/dm3] 3)	1,8	2,07	1,43	1,68
BOILING POINT [°C] 4)	-3,9	-22,5	-17	56

1) referred to R 11
2) referred to CO_2
3) at 25°C
4) at 1013 hPa
5) unknown

Fig. 1: Physical and Environmental Properties of the tested Agents

5. FIRE TESTS

5.1 AIRCRAFT CARPET FIRE TESTS

The experiments were conducted at the DLR test facility in Trauen in a full-scale cabin mock-up. It is an Airbus A 300 similar fuselage quarter section with 3m radius and 6m length and is made of steel. Fig. 2 shows the mock-up.

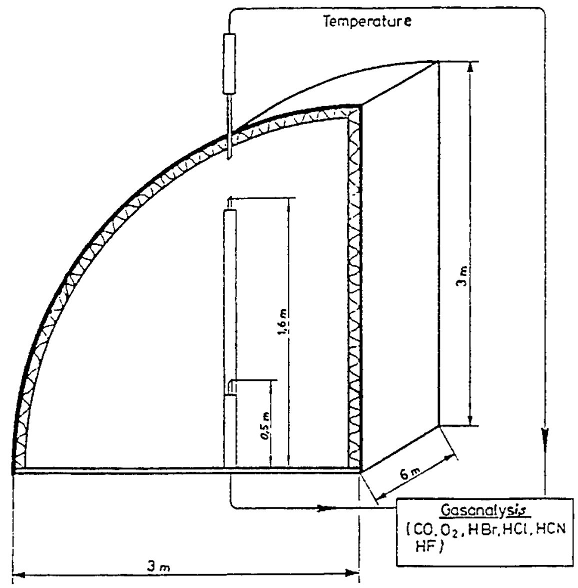

Fig. 2: Cabin Mock-up for Aircraft Carpet Fire Tests

Inside the cabin, an area of 2m x 2m was layed out with used carpet of a Boeing 747. It was drenched with 4 liters of gasoline and then ignited. After a preburn time of 30s it was tried to extinguish the fire.

6kg handheld extinguishers were used so that no change of the extinguisher during the test was necessary. So the extinguishing time and the mass could be determined exactly. All used extinguishers were filled with 6kg of the agent. Only the FM 200 extinguishers were filled with 4kg because of the agent's lower density. Nitrogen was used as propellent, with a pressure of 10bar for FM 200 and CEA 614 and 15bar for Triodide and Halon 1211. The propellent pressure and the nozzles were determined in accordance with the agent manufacturers' specifications. FM 200 was used with an ordinary Halon 1211 nozzle, Triodide with the same nozzle with 25% bigger orifice diameter. For the CEA 614 a wide angle nozzle was used because this agent needs a special processing due to its physical properties.

Besides extinguishing time and mass consumption, the carbonmonoxide- and oxygen-concentrations inside the test cell were measured, furthermore the four toxic gases HBr, HCl, HF and HCN.

5.1.1 RESULTS: EXTINGUISHING TIME

The comparison of the achievable extinguishing times are shown in Fig. 3. All given values are the average of 6-7 experiments.

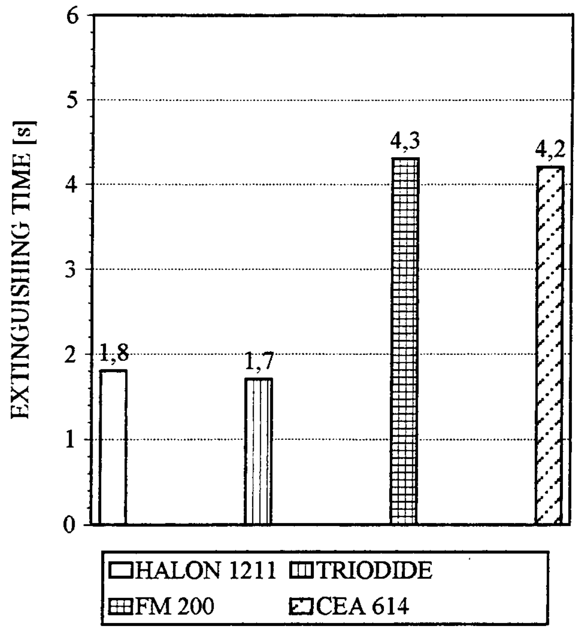

Fig. 3: Aircraft Carpet Fire Tests: Extinguishing Time

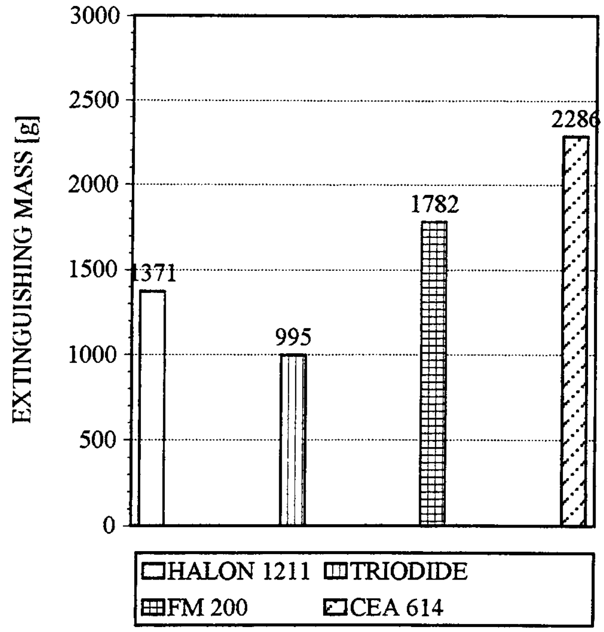

Fig. 4: Aircraft Carpet Fire Tests: Extinguishing Mass

The reference agent Halon 1211 baseline is at t=1.8s with a standard deviation of σ=0.27s which means an extremely low scattering. Using Triodide a comparable extinguishing time of t=1.7s is achieved. The standard deviation is at σ=0.44s. The average extinguishing time for FM 200 is t=4.3s, clearly higher than the Halon 1211 and Triodide values. Its standard deviation is at σ=1.2s. At the same level is CEA 614. Its average extinguishing time is t=4.2s with a high deviation of σ=2.0s.
Concerning extinguishing time for aircraft carpet, obviously only one of the agents reaches the qualities of Halon 1211. The Triodide data are quite similar in short extinguishing time and small standard deviation.

5.1.2 RESULTS: EXTINGUISHING MASS

By weighing the extinguisher before and after the test the mass consumption was determined. The average values are plotted in Fig. 4.
The baseline of the reference extinguisher Halon 1211 is at m=1371g with a standard deviation of σ=232g. Even better is Triodide with an average value of m=995g but σ=330g. FM 200 follows with m=1782g and σ=333g. For CEA 614 the values are 2286g and 576g respectively.
The results are similar to those of chapter 5.1. Again Triodide is at the Halon 1211 level, but with a higher standard deviation. At a clearly higher level are the values for FM 200 and CEA 614. .

For better classification of these results Fig. 5 shows the equipment of Halon 1211 handheld extinguishers in civil passenger aircrafts in Germany (/10/).

AIRCRAFT TYPE	COCKPIT	CABIN	CARGO COMP.
AIRBUS A 300-600	1 x 1 kg	8 x 1 kg	1 x 2,5 kg
AIRBUS A 310	1 x 1 kg	6 x 1 kg	1 x 2,5 kg
AIRBUS A 320 AIRBUS A 321	1 x 1 kg	4 x 1 kg	(-)
AIRBUS A 340-200 AIRBUS A 340-300	1 x 1 kg	8 x 1 kg 1 x 1 kg CREW REST	1 x 2,5 kg
BOEING 737-200 BOEING 737-500	1 x 1 kg	3 x 1 kg	(-)
BOEING 737-300 BOEING 737-400	1 x 1 kg	4 x 1 kg	(-)
BOEING 747-200	1 x 1 kg	11 x 1 kg	1 x 2,5 kg
BOEING 747-400	1 x 1 kg	16 x 1 kg	1 x 2,5 kg
MD DC-10	1 x 1 kg	10 x 1 kg	1 x 2,5 kg
MD-11	1 x 2,5 kg	7 x 2,5 kg	(-)
LOCKHEED L-1011	1 x 2,5 kg	6 x 2,5 kg	(-)

Fig. 5: Equipment of Handheld Extinguishers in Civil Passenger Aircrafts

At least for the smaller aircrafts the security factor seems to be quite low. It must be considered that a real fire possibly can't be extinguished with only one extinguisher. A smaller extinguisher means a smaller agent's mass and as well a smaller mass flow rate to fulfil the extinguisher's stipulated discharge time. This time depends on the rating-class and is at least 8s, see for example /11/.

Probably the extinguisher has to be changed during the extinguishing, which may lead to a regrowth of an already controlled fire. Further must be considered that the extinguishers which are located at the doors of the aircraft must be provided by servants in time. Even if two or more crew members try to extinguish the fire simultaneously, the available mass flow may be too small so that the necessary concentration to extinguish the fire is not reached.

5.1.3 RESULTS: OXYGEN- AND CARBONMONOXIDE-CONCENTRATION

The test cell is equipped with two measuring probes at 50cm and 160cm height above the cabin floor. During the tests the carbonmonoxide- and oxygen-concentrations were measured continuously. The maximum CO- and minimum O_2- concentrations which were measured are plotted in Fig. 6 and 7. The given concentrations refer to the volume of the in chapter 5.1 described test cell.

All data are average values and were taken at the upper measuring probe. At the lower one, no significant gas concentration could be detected, an often seen phenomenon with fires.

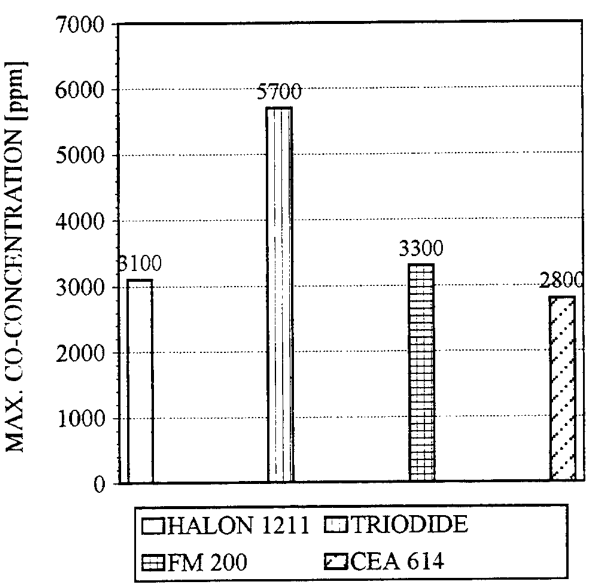

Fig. 6: Aircraft Carpet Fire Tests: Max. CO-Concentration

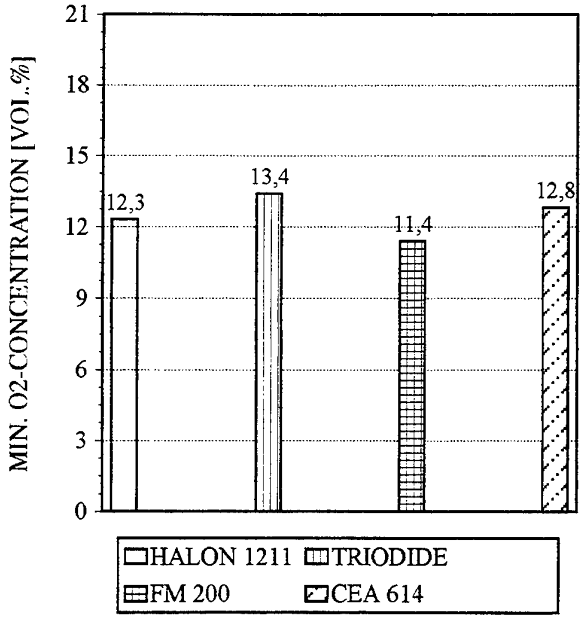

Fig. 7: Aircraft Carpet Fire Tests: Min. O_2 - Concentration

Although the extinguishing time was the shortest with the Triodide the highest CO-concentrations were obtained (5700vol.ppm). Halon 1211 and the two other agents were at about the same level (Halon 1211: 3100ppm, FM 200: 3300ppm and CEA 614: 2800ppm). For a better understanding of the data Fig. 8 shows the allowed CO-concentrations in breathing air (/12/).

CO [ppm]	RESIDENCE TIME
3000	MINUTES
1600	0,5 HOURS
800	1 - 2 HOURS
100	8 HOURS

Fig. 8: Allowed CO-Concentrations in Breathing Air

Quite close to each other are the minimum oxygen-concentrations inside the cabin. The highest oxygen depletion is seen with FM 200 (the remaining oxygen-concentration is 11.4 vol.%). Halon 1211 follows with 12.3vol.%, CEA 614 with 12.8vol.%. The highest remaining oxygen-concentration is seen with Triodide (13.4vol.%). Fig. 9 shows the dangers of decreasing oxygen-concentration in breathing air (/12/).

O2 [VOL.%]	EFFECT
21	NONE
17	IMPAIRED MUSCULAR CO-ORDINATION
14	DANGER LEVEL FOR SELF-ESCAPE
12	DIZZINESS, HEADACHE, RAPID FATIGUE
9	UNCONSCIOUSNESS
6	DEATH IN 6 - 8 MINUTES

Fig. 9: The Influence of Decreasing O_2-Concentration in the Breathing Air

5.1.4 RESULTS: TOXICITY ANALYSIS

The measurements for the determining of the emitted toxic gases hydrogen bromide (HBr), hydrogen chloride (HCl), hydrogen fluoride (HF) and hydrogen cyanide (HCN) were taken discontinuously. The samples were taken in gas-wash-bottles, analyzed with ion-selective-electrodes and finally calculated to volume concentrations.

Comparable to the carbonmonoxide- and oxygen-measurements, significant data could only be taken at the upper probe.

The average results (referred to the test cell's volume) are shown in Fig. 10. It should be generally noticed that by the fire of the carpet itself (without extinguishing) high concentrations of HCl, HBr and HCN occured that those due to the use of the extinguishing agents could be neglected. Further has to be noticed that only the Halon 1211 let expect bromine- and chlorine-concentrations because of its molecular structure. The three alternatives only contain the halogen fluorine (Triodide additionally iodine).

	HALON 1211	TRIODIDE	FM 200	CEA 614
HF [ppm]	*	60	10	60
HCl [ppm]	*	*	*	*
HBr [ppm]	*	*	*	*
HCN [ppm]	*	*	*	*

*: Under Value of Pure Carpet Fire

Fig. 10: Aircraft Carpet Fire Tests: Toxicity Analysis

The measured HF-concentrations show very high values for Triodide and CEA 614 of 60ppm. The values for FM 200 are much lower (10ppm). The data for Halon 1211 are lower than the values of pure carpet fire.

Fig. 11 shows the allowed human limiting values (/13/) for hydrogen fluoride.

HF [ppm]	EFFECT
50 - 100	LETHAL FOR 30 - 60 MINUTES RESIDENCE TIME
30	CAUSTIC IRRITATING SMELL
3	MAK *)

*) Maximum Allowed Concentration at Working Place

Fig. 11: Allowed Human Limiting Factors for HF

5.2 AIRCRAFT SEAT FIRE TESTS

For these tests used original aircraft seats were burned. To avoid the influence of burning plastic parts of the seat construction, only cushion and back rest were mounted on a rack and drenched with 1 liter gasoline. After a preburn time of 60s the fire was extinguished with the handheld extinguishers. During these tests the fire worker sometimes had to extinguish in gushes for an optimal extinguishing attack. Fig. 12 shows the test set-up, Fig. 13 the extinguishing.

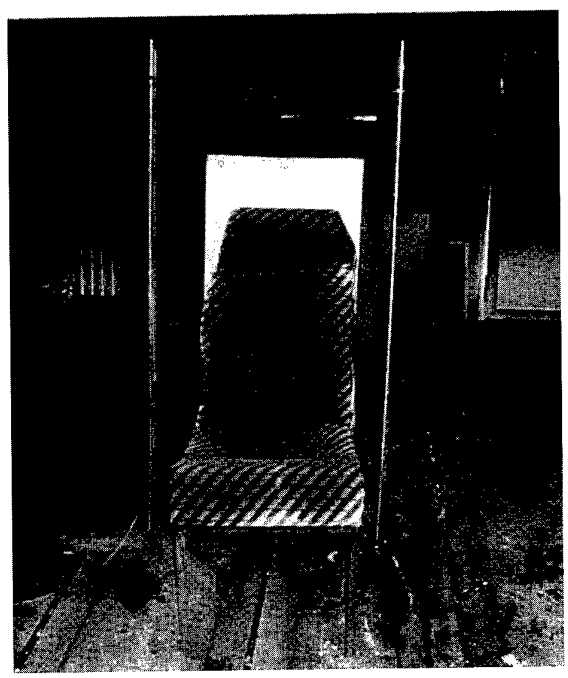

Fig. 12: Test Set-Up for Aircraft Seat Fire Test

Fig. 13: Aircraft Seat Extinguishing

Due to the enormous fire which developed inside the test cell during the carpet fire and the risk for the fire worker, these experiments took place in a one side opened room. Extinguishing time and mass were analyzed.

5.2.1 RESULTS: EXTINGUISHING TIME

The results are shown-up in Fig. 14. Halon 1211's baseline is at t=1.4s for the extinguishing of the seat fire with a standard deviation of σ=0.45s. Nearly identical are the values for Triodide with t=1.5s and σ=0.37s. Clearly higher are the values for FM 200 (t=2.5s, σ=1.11s) and CEA 614 (t=3.3s, σ=0.77s), which means longer time but smaller standard deviation for the CEA.

Again similar to the carpet fire, only the Triodide comes close to the Halon 1211 baseline in extinguishing time and as well in the scattering of the values.

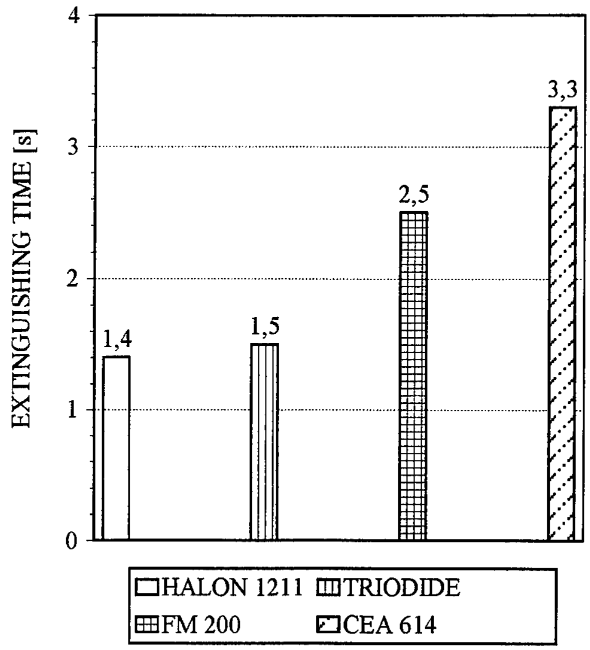

Fig. 14: Aircraft Seat Fire Tests: Extinguishing Time

5.2.2 RESULTS: EXTINGUISHING MASS

The mass consumption is shown in Fig. 15. m=651g with σ=69g is the baseline for Halon 1211. Although similar in time, clearly more agent mass has to be used with Triodide (m=1126g and σ=187g). FM 200 with an extinguishing mass of m=943g and σ=151g is between Halon 1211 and Triodide. The largest mass was needed with CEA 614 (m=1758g, σ=229g).

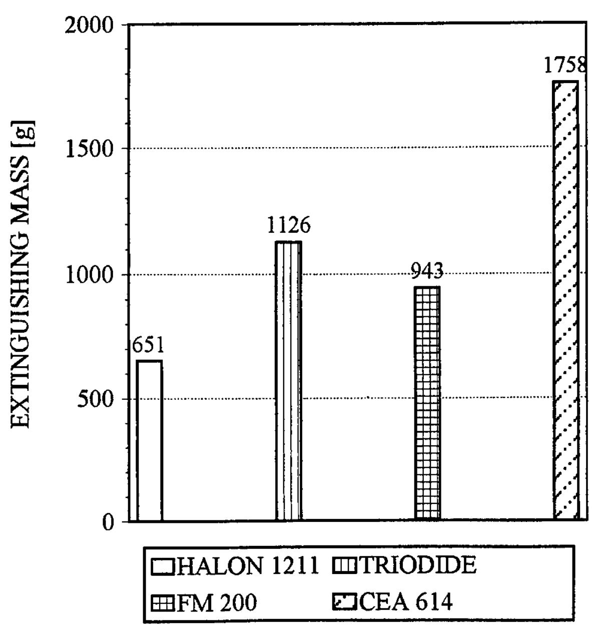

Fig. 15: Aircraft Seat Fire Tests: Extinguishing Mass

5.3 HIDDEN FIRE TEST METHOD

To examine the different agents under labour scale conditions, a test mock-up was constructed which allows the extinguishing of fires using small amounts of the agent. In its vertical part, the mock-up contains two rows of premixed propane/air fed flames, the lower one with 11, the upper one with 10 flames. In the horizontal part, the inlet is blocked by a labyrinth. Fig. 16 shows the design of the set-up. The top of the chimney is open. On its underside are drilled holes which increase the difficulty for the agent to reach the flames. The complete set-up is shown in Fig. 17.

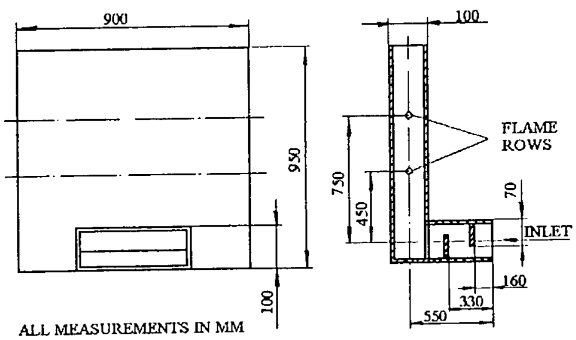

Fig. 16: Hidden Fire Set-up Design

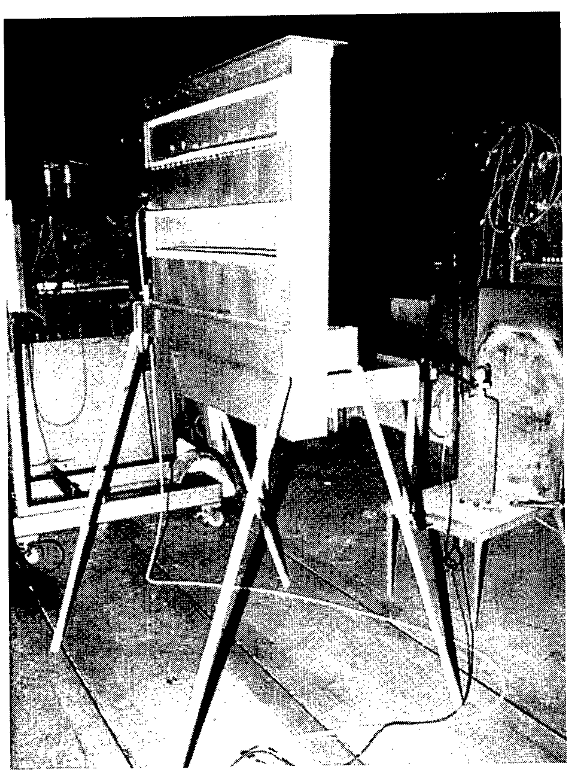

Fig. 17: Set-Up for Hidden Fire Tests

This construction simulates a fire inside an aircraft cabin behind the side wall panel with all its obstacles which is tried to be extinguished through the ventilation opening. This case became real 1992 during a Delta Airlines inflight fire over the Atlantic Ocean, where the crew could manage to extinguish the fire exactly this way using three 2.5kg Halon 1211 extinguishers. Since then experts think this scenario to be a good test to investigate the qualities of possible halon-alternatives extinguishing hidden fires.

Ordinary handheld extinguishers were used, each of them equipped with a halon nozzle of 1mm orifice diameter. Due to the agent's special physical properties the CEA 614 extinguisher was equipped with a wide angle nozzle of as well 1mm orifice diameter. The nozzle of the extinguisher was mounted 10cm in front of the inlet. The discharge of the agent into the channel was controlled by an electrically driven valve together with an electronic timer.

The number of extinguished flames was observed through two windows on the rear of the chimney. The extinguishers were mounted on a weigher to determine the discharged mass of the agent.

5.3.1 RESULTS

Fig. 18 shows the relation between the number of extinguished flames in dependence on the needed mass of agent. Each curve is made from about 50 measurings. On the lower part of the figure (flames 1 to 11) the results for the lower flame row are shown.

The first increasing and steepest curve belongs to Halon 1211 which means highest extinguishing efficiency, the most extinguished flames with the lowest agent's mass. Quite close to that comes Triodide, for which the curve starts early as well. Then, about 50 gramms shifted to the right, the FM 200 curve starts to rise. Nearly parallel to this curve but shifted about 100 gramms are the results for CEA 614.

For the upper row of flames (flames 12 to 21) the correlation changes slightly. The first increase and therefore best efficiency shows Triodide. Halon 1211 shows an approximately parallel curve, but shifted 50 gramms to the right. An even earlier increase than Halon 1211 shows FM 200, but with a less steep curve. Clearly less effective in the upper row is CEA 614 which shows a far shifted and flat curve.

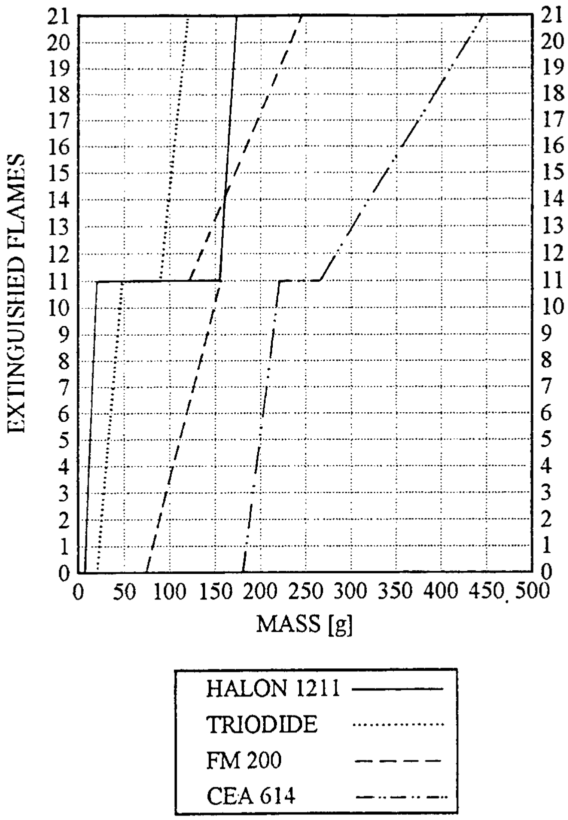

Fig. 18: Hidden Fire Tests: Number of the Extinguished Flames in Dependence on the Extinguishing Mass

6. CONCLUSIONS

Concerning extinguishing mass and extinguishing time, only one of the alternative agents came close to the Halon 1211 baseline. Only Triodide allowed a similar fast and safe extinguishing success. The scattering of the measuring values (standard deviation) was nearly as good as with Halon 1211.

Of course, with both other alternative agents it was possible to extinguish the examined fires, too. But they showed bigger scattering and worse extinguishing efficiency than Halon 1211 or Triodide.

Besides extinguishing efficiency there are other important criteria to be considered, for example environmental and human aspects. Triodide, the alternative agent with the best extinguishing properties has by far the worst NOAEL and LOAEL, which stand for cardiac sensitization. The possible use of this agent inside person-occupied areas is at least questionable. It showed as well critical toxicological properties during the here described tests. Rather unproblematic seems its use for aircraft engine extinguishing systems. The Triodide molecule has a very short atmospheric lifetime and therefore it has no global warming potential. Its ozone depletion potential is nearly zero. Triodide is by far the most expensive one compared to the other tested agents including Halon 1211.

The agent with the poorest extinguishing efficiency, CEA 614, shows the best properties concerning cardiac sensitization, which is important for the possible use inside person-occupied areas. But its molecule has an extraordinary long atmospheric lifetime and therefore a very high global warming potential. Its ozone depletion potential is zero.

Concerning cardiac sensitization FM 200 is situated between the two other alternative agents. The same is valid for its global warming potential. Its ODP is zero. FM 200 doesn't reach the extinguishing efficiency level of Halon 1211 or Triodide. Here as well it is located between the two and CEA 614.

As there are several criteria to consider, it is not easy to make a safe decision for the benefit of an agent or not. Each of them has distinct advantages and disadvantages.

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DISCUSSION - PAPER NO. 14

C.A. Kirk (Question)

Has there been any similar testing to that discussed in this Paper using HFC-125 (FE-25)?

K.M. Kallergis - Author/Speaker (Response)

To my knowledge, there has been no fire tests with FE-25 in Germany. I am waiting for the delivery of FE-25. After running tests with it, results will be available via the International Halon Replacement Working Group, and via myself.

L. Ernst (Question)

Hidden flame test: What is the reason for using less amount of Triodide compared to Halon to extinguish the upper flame row?

K.M. Kallergis - Author/Speaker (Response)

Obviously, Triodide shows a better vaporization and spreading in the upper part of the test set-up. That is the reason for the higher number of extinguished flames with less injected mass.

J.P. Van Wuÿckhuise (Question)

Can you say something about the toxic effects of the extinguishing agents you showed us (extinguishing concentration, temporary or definitive)?

K.M. Kallergis - Author/Speaker (Response)

I dont have all the data with me but, if you leave me your address, I will send you the desired information. (Please also note the the Paper by A. Mansuet and J.-F. Petit of CEAT, and the lecture by D. Dierdorf from Pacific Scientific.)

P. Derouet (Question/Comment)

1) In the table (ref. fig. 5), what is the mass of the fire extinguishing systems for the engine compartments?

2) I have a recommendation: People who try to find products in replacement of Halon must take into account the fact that, in case of false detection, when the pilot activates the engine fire extinguisher, such products (presently Halon) can attack engine casings and mounts (especially casings made of titanium). The fire extinguishing agent must therefore be non-corrosive for the engine and pod.

K.M. Kallergis - Author/Speaker (Response)

2): It is clear that corrosiveness is an important point, not only in the engine area.

1) & 2): Please leave me your address and I will send you the desired information.

A. Mulda (Question)

Does the production of HF during fire extinguishing depend on the available amount of extinguishing medium (FM-200, etc.) (e.g. if the amount of medium is not, or just enough, to extinguish the fire)?

K.M. Kallergis - Author/Speaker (Response)

All of the fires examined were extinguished without any failure. Of course, it was attempted to extinguish the fire in the shortest possible time (= just enough mass). I can't say if this influences the generation of HF, but I know of fire trials by the FAA which yielded higher HF concentrations, especially for FM-200.

HALON REPLACEMENT - AVIATION TEST CRITERIA

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United Kingdom

INTRODUCTION

Halon is widely used in civil aircraft. In a typical wide body jet aircraft passengers will be protected by both Halon 1301 and Halon 1211. Over the past 30 years, because of its exceptional fire fighting performance, relative low cost, ready availability and low weight and volume to effectiveness, Halon 1301 has evolved as the agent of choice. A vast amount of testing has been done during that period to certificate Halon fire suppression systems in engine nacelles, auxiliary power unit compartments, trash containers, and cargo compartments of various size and shape. In addition, Halon 1211 in hand held extinguishers has been found to be very effective in fighting the most hazardous of in-flight fires.

Cargo compartment fire suppression.

In modern large passenger aircraft in which cargo compartments have a volume greater than 1000 cubic feet these areas are protected with fixed fire extinguishing systems. An uncontrolled fire in a cargo area may cause fumes and smoke to penetrate into the cabin and heat from the fire could disable vital functions of the aircraft controls. To protect against this possibility both passive and active defences are utilised. The cargo compartment is lined with fire resistant panels that will help to prevent the spread of fire outside of the compartment and the airflow into and out of the compartment is controlled. In addition the compartment will have smoke detectors fitted which in the event of a fire will alert the crew and enable them to activate the fire suppression system.

The extinguishing agent must be compatible with aircraft materials and electrical systems, it should not be dangerously toxic, nor should it settle or stratify when released. The extinguishing agent must have a rapid knockdown capability and then maintain continued protection for a period of time until the aircraft can safely land, this could be three hours. Halon 1301 meets all of these requirements, a typical wide body aircraft will carry 60 kg. The rapid knockdown and continued protection can be achieved with an initial concentration of 5% and thereafter 3%.

Engine power plant fire extinguishment

Halon 1301 is also used for fire extinguishing systems in aircraft power plants (the area around the core of the engine in which electrical generators, igniters, hydraulic pumps, oil and fuel systems may be found) Fires may occur during any phase of operation, the physical properties of Halon 1301 are therefore very important in this application. The agent must discharge extremely rapidly and expand within the engine nacelle over the full range of ambient pressures and temperatures that an aircraft may experience. Fires occurring at flight speeds can rapidly become very intense, engines are necessarily located close to, and supplied with, large quantities of fuel. A fire needs to be quickly controlled. A typical wide body twin engined aircraft would have 15 kg of Halon 1301 installed to protect the engine installation.

Hand held fire extinguishers

Halon 1211 is used for the protection of aircraft and passengers from fires arising in the cabin or cockpit. Hand held portable extinguishers, usually with 1.5 kg of agent, will be strategically positioned throughout the cabin and flight deck for use by the flight crew and cabin staff. Fires arise from many sources, typically; cigarettes, ovens, non safety matches and electrical fires. There are documented incidents where, if it were not for the capability of Halon 1211 to extinguish fire in inaccessible locations, the aircraft and passengers would most probably have perished. The extinguishing agent must be non toxic to occupants. The agent must be safe to use in the flight deck of an aircraft whilst in flight with no risk of causing instruments and controls to fail due to electrical or material incompatibility. It must not generate dust or smoke which may obscure instruments or vision out of the aircraft. Minor in flight fires occur relatively frequently, typically there have been 20 per year reported in UK passenger aircraft during recent years. Whilst the flight and cabin crews have to undertake training in the use of the portable fire extinguishers aboard their aircraft they cannot be considered to be "trained fire fighters". Therefore an agent is required that will be effective even if the method of application may be less than optimum. A typical wide body aircraft would require twelve 1.5 kg Halon extinguishers. (Sometimes water extinguishers are also carried, these have particular capabilities such as the cooling and dampening down of potential fuel sources following a fire incident.).

The aviation authorities have two key roles to play in the transition away from Halon. Firstly they must use their influence to ensure that the Aviation Industry is fully informed of all the issues concerning the continued use of Halon, and that the environmental legislators understand the needs of aviation and the potential serious safety implications if Halon were withdrawn from use without alternatives having been developed. Secondly they must assist the Industry in the search for acceptable alternatives by ensuring that practicable methods of certificating alternatives agents and systems have been developed.

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

The CAA has played a lead role in ensuring that the interests of the UK aviation industry have been presented to the Department of Transport and Department of Environment. The CAA assisted in the formation of the Halon Users National Consortium (HUNC), the organisation which enables trade in recycled Halon. It was recognised that recycling and the trading of existing agent would form an essential element in a well managed and safe transition away from Halon. Additionally by reviewing its own requirements the CAA has helped prevent unnecessary use of Halon. By initiating the production of a video detailing the use of Halon 1211 extinguishers the CAA has been able to make changes to the training syllabus for cabin and flight crews so that it is no longer necessary for them to discharge Halon when training.

The aviation authorities in their design requirements strive to define safety objectives and performance standards rather than prescribe specific solutions. In this manner Industry is then able to develop the optimum solution for any particular application taking full advantage of new technologies. Apart from an operational requirement that stipulates the quantity of Halon 1211 extinguishers to be carried in passenger aircraft, there is no requirement that states Halons must be used. However, due to the nature of the Halon agents and their very high performance these agents became the natural choice and it was never necessary to develop detailed acceptance criteria to cater for alternative agents and systems. Now, with the production ban on both 1301 and 1211, it is necessary to define the performance of current Halon systems and set minimum performance requirements for alternative systems. This is not a simple task, for Halon will not necessarily be replaced by similar agents. An entirely different approach to achieving the current safety standards may be adopted. As an example, it has been suggested that future engine installations could be designed with fireproof barriers so that in the event of fire all fuel and oil supplies would be isolated and the fire allowed to burn out without risk to the airframe.

The aviation authorities must decide whether to accept the performance of Halon as the minimum level of safety (that is any replacement must perform as good in all parameters as the Halon it is replacing) or whether to accept a level independently derived from a determinate of tolerance limits for both passengers and airframe, or a combination of the two.

As an example the following is a list of some of the questions concerning cargo compartments which need consideration :

1. Toxicity. Is the killing of humans or animals by an accidental discharge acceptable? A CO2 or Nitrogen inerting system could do this.
2. If the agent were corrosive would it be acceptable?
3. Would damage to cargo be a major concern?
4. Is volume of agent a problem? The greater the volume of agent pumped into the cargo compartment the more combustion by-products will be pushed out of the compartment and possibly forced into the passenger cabin.
5. Maximum temperature in a compartment. Halon 1301 and anticipated replacements will suppress most Class A fires. They do not necessarily extinguish them. Should the allowable smouldering rate (this would equate to temperature in the compartment) be equal to or less than when 1301 is used?
6. It has been shown that Halon 1301 will suppress the explosive combustion of an aerosol can (which now typically use butane or propane as the propellant instead of CFCs) Must a replacement agent also protect against the possibility of aerosols exploding if they were near to a fire?

Questions such as these are very difficult to answer without knowledge of possible alternative agents and systems and an indication from the airlines and aircraft manufacturers as to what they consider to be acceptable. As a result of discussions between the aviation authorities the US Federal Aviation Administration in their Public Notice 93-1 published in the Federal Register 17 June 1993, announced a proposed research programme to develop performance test methodologies which would lead to recommended airworthiness criteria for the evaluation of non-Halon fire suppression agents and systems to be used aboard aeroplanes and rotorcraft.

To support this activity the FAA invited any interested organisation to join an International Halon Replacement Working Group (IHRWG). The purpose of the working group is to assist the aviation authorities in the development of certification criteria for future non-Halon fire protection systems on aircraft.

The IHRWG is an informal group composed of chemical companies, fire protection system manufacturers, airframe manufacturers, engine manufacturers, researchers, operators and regulators. In this forum issues can be openly discussed and quickly resolved to enable the necessary information to be available to guide research and regulatory decisions that will be made by the Authorities.

AN EXAMPLE OF THE DEVELOPMENT OF HALON REPLACEMENT - AVIATION TEST CRITERIA

I would like to take one area of fire protection on an aircraft and use that as an example to illustrate how the selection criteria for non halon fire protection have been derived. The UK Civil Aviation Authority was responsible for research in the area of handheld extinguishers and I will therefore use this specific use of halon as my example.

Three questions were key to the identification of the important criteria.

1. Why carry handheld extinguishers on aircraft?
2. Why use Halon 1211 as an extinguishing agent?
3. How do we ensure no loss in safety?

Why carry handheld extinguishers on aircraft?

The design philosophy adopted by all manufacturers and reinforced by the airworthiness requirements is to minimise the likelihood of a fire occurring. This aim is achieved by a number of different means; only materials which are heat and fire resistant or fireproof are used in areas considered to be vulnerable, the location of potential ignition sources is carefully controlled. Flammable fluids are similarly kept well away from heat and electricity. In addition to these physical measures there are also procedures adopted by the operators of the aircraft, these range from ensuring the integrity of

systems during routine maintenance, the cleaning of dust and rubbish from the cabin and air return grilles, to the purposeful checking of lavatories regularly during flight for any signs of smoke or fire. Further restrictions are placed on passengers to ensure that they do not bring hazardous materials onto the aircraft and to control smoking to only those occasions when they are seated.

However as we all know things can and do go wrong and the unexpected happens, it is on these occasions that the adaptable and resourceful human being can be invaluable, provided they have a capable fire extinguisher available to them. This is the reason that handheld extinguishers are carried on aircraft.

There are incidents recorded which demonstrate the need to cater for the unexpected:

> "Passenger dropped cigarette into bag of passenger seated behind. Bag immediately caught fire and set the surrounding carpet alight".

> "Passenger stowed a bag containing a chainsaw in overhead locker, gasoline seen dripping from locker"

Why use Halon 1211 as an extinguishing agent?

To effectively answer this question it is necessary to consider the alternative agents. Across all applications water is the most commonly used fire fighting agent, it also has a role in aviation and is used in aircraft cabins. It cannot be used on electrical or fuel fires but is very good in extinguishing class A fires such as trash container fires consisting of burning paper. It is excellent at cooling materials and preventing re-ignition.

Carbon Dioxide (CO_2) extinguishers have been used on aircraft in the past but have very limited class A fire fighting capability in relationship to the size and weight of the required extinguisher. They cannot be used safely on electrical equipment because of the risk of thermal shock from the dry ice expelled by the extinguisher.

Chemical Powder extinguishers suffer from many disadvantages. The powder when discharged forms a cloud restricting visibility, thus they cannot be used in the cockpit of an aircraft, in addition the powder when it settles would cover instrument faces making the instruments unreadable. The powder can cause electrical failure of switches (usually by insulation of the contacts) and finally the residue is corrosive to an aircraft structure and components, and therefore requires very careful cleanup after a discharge.

Halon 1211 is very effective on fuel fires (class B), has quite good class A fire fighting ability and can be used on fires involving electrical energization (class C). It is not very critical with respect to operator technique and the agent is relatively efficient which enables the extinguisher to be physically quite small. The use of water to dampen a fire after extinguishment with Halon 1211 is recommended. As noted by Krasner[1] there are many sources of water available in an aircraft cabin, including coffee and soft drinks.

In August 1980 a new FAA Advisory Circular 20-42A was issued entitled "Hand Fire Extinguishers for Use in Aircraft" this indicated the acceptability of an Underwriters Laboratory (UL) toxicity rating of 5 or higher and for the first time allowed for the use of Halon 1211. At approximately the same time a series of hijackings took place, all using volatile liquid as the threat. The FAA Technical Centre in Atlantic City conducted a series of tests and in November 1980 a general notice was issued which encouraged operators to carry at least two Halon 1211 extinguishers. The tests conducted at this time demonstrated that Halon 1211 was the best available agent[2] and that potential toxic breakdown products were not an additional hazard[3].

Halon 1211's full chemical name is Bromochlorodifluoromethane or BCF for short. It is a liquid when stored at pressure, which is typically 130 psi for an extinguisher, but has a boiling point of -4 degrees centigrade. It is thus a gas at room temperature. In practice the agent leaves the extinguisher primarily as a liquid which enables it to be directed towards the fire, it then rapidly evaporates to become a gas. It acts chemically to prevent combustion and requires only 3.5% concentration to achieve this. It is thus easy to use and forgiving of poor fire fighting technique.

In ground based applications Halon 1211 is acceptable for use as a hand held extinguishant but not for fixed systems in occupied spaces due to its toxicity. However the tests previously mentioned[3] demonstrated that a more toxic agent that puts the fire out very quickly with the use of only a small quantity of agent could be safer for passengers in the cabin than a less toxic but less effective agent. This is because the hazard that the passenger has to endure is the combination of the toxic threat of the agent and its breakdown products together with the toxic threat of the combustion products from the fire, and it is the fire which rapidly becomes the most extreme hazard.

Toxic threat of the agent + Toxic threat of thermal breakdown products of the agent + Toxic threat of fire products = Gross toxic threat to passenger.

Past experience of fires in aircraft cabins confirm that it is rare for a fire to occur. The statistics also confirm that the vast majority of incidents are readily resolved by the flight attendants. Table 1 records the percentage of reports of smoke or fire by location within the cabin. Table 2 records the percentage of actual discharge of extinguishers by location within the cabin. By comparison of the number of incidents recorded for each of the two tables it can be surmised that many incidents, particularly those related to the galley, are resolved without the need for an extinguisher.

Location in Cabin	Percentage
Galley	67%
Passenger Cabin	16%
Lavatory	10%
Flight Deck	5%
Overhead Area	1%
Cargo	1%

Table 1 Reports of Fire or Smoke

Location in Cabin	Percentage
Passenger Cabin	32%
Galley	27%
Lavatory	27%
Flight Deck	9%
Other	6%

Table 2 Location of Fire or Smoke

Ignition Source	Percentage
Electrical	38%
Cigarette	28%
Not recorded	15%
Oven	7%
Other	11%

Table 3 Reports of Ignition Source

From reading the description of the events it is clear that in only a very small percentage of the incidents is the location of the fire not immediately evident. The majority of the data above was recorded prior to the more widespread restrictions on smoking. There is now some evidence developing which suggests that incidents in the passenger cabin are diminishing whilst reports of illicit smoking in lavatories is increasing.

The Cincinnati DC9 accident of 2 June 1983 clearly demonstrates that the most dangerous fire is one that is hidden from the cabin. Figure 1 illustrates what is meant by "hidden" areas, these are the cheek areas, the overhead and underfloor voids and the area behind sidewalls. In this accident an in-flight fire in a lavatory developed behind the sidewall. One CO_2 extinguisher was discharged into the lavatory from the cabin. The fire continued to increase in size and the cabin progressively filled with smoke. The aircraft landed safely, however there were 23 fatalities during the evacuation as the fire "flashed" in the cabin.

More recently in March 1991 an L1011 aircraft flying from Frankfurt to Atlanta whilst carrying 226 people experienced an in-flight fire at 33,000 ft and 200 miles from the nearest place to land. A fire in the cheek area was started by an overheating electrical cable but fuelled by dust, dirt and debris below the floor, flames 2 feet high entered the cabin. This fire was extinguished by injecting three Halon 1211 extinguishers through return air grilles at floor level. The aircraft made a safe landing at Goose Bay, Newfoundland. It is incidents such as this which re-affirm the need to carry Halon 1211 extinguishers on public transport aircraft.

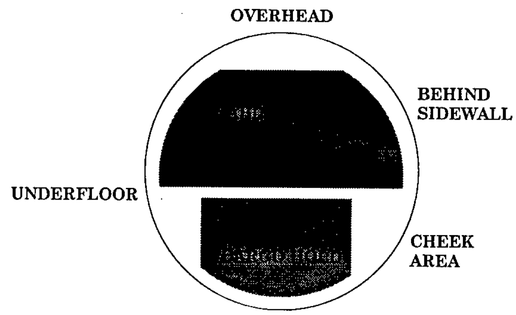

Figure 1 Cross Section of Fuselage Illustrating Hidden Areas

How do we ensure no loss in safety?

If the change from halon is to be made without incurring any drop in safety then it is necessary to define the capability of the current extinguishers and ensure that replacements have equal or better performance. In part this can be achieved by ensuring that the extinguisher is approved by an organisation such as Underwriters Laboratories or Factory Mutual, or meets a defined standard, for example British Standards Institute or EN - Euro-Norm. This will ensure that the extinguisher has a basic defined fire fighting performance. In addition it will be necessary that the extinguisher must demonstrate the capability to deal with the specific threats peculiar to aviation. These threats could be a large fires that results when flammable fluid is splashed on a passenger seat and ignited or when a fire develops in a hidden area. Further considerations will be; ease of use and training, and the assurance that no additional hazards are introduced as a result of the new agent.

To ensure that the objectives outlined above could be defined in detail the Aviation Authorities agreed that both research effort and industry involvement was required. As part of this International effort the UK Civil Aviation Authority agreed to pursue the development of a representative hidden fire test method as none existed previously.

Following an invitation for competitive tenders to develop a standard hidden fire test protocol, the Civil Aviation Authority awarded a contract to Kidde International Research.

The basic methodology was to replicate the volumes, airflow rates and physical restrictions found in the hidden areas of a fuselage. Comparison of figures 2 and 3 will illustrate how this has been achieved.

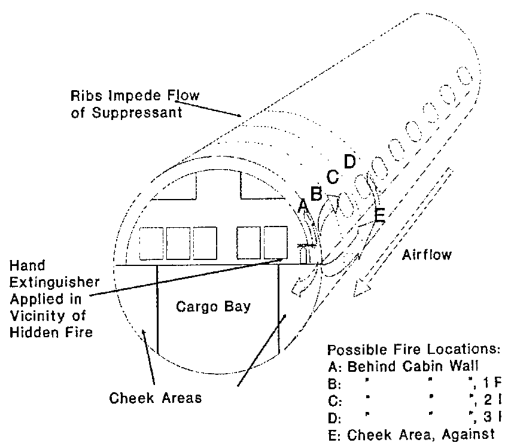

Figure 2 Hidden Areas within the Fuselage

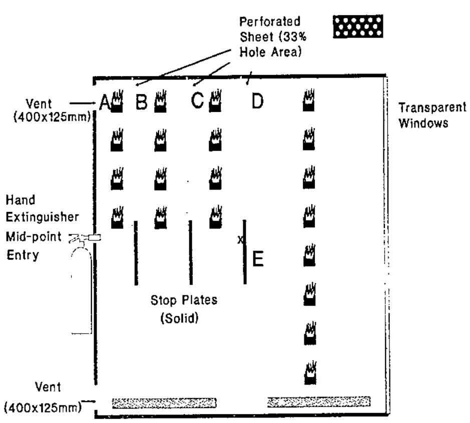

Figure 3 Illustration of Hidden Fire Test Chamber. Measuring 2m x 2m x 0.5m

Figure 4 illustrates how the test method can then be used to "map" the effectiveness of an extinguisher and agent by observing extinguishment of the test fires.

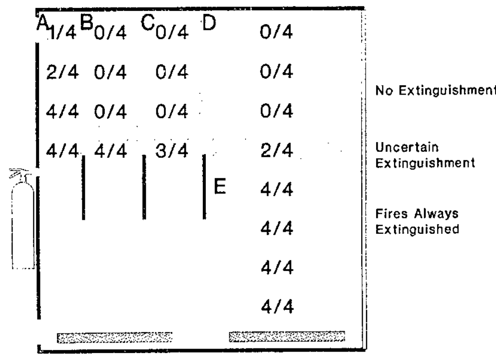

Figure 4 Test Results for 2 1/2 lb. Halon 1211 Extinguisher

Tests have been carried out with hand extinguishers from Walter Kidde, Kidde Thorn, First Technology and Chubb. Results varied from 45% extinguishment to 60%, depending on the quantity of Halon contained in the extinguisher, and the discharge rate (a faster discharge rate creates more turbulence, aiding mixing and dispersion). In addition, tests were carried out using under- and over-filled extinguishers to examine the sensitivity of the test method. With the exception of the First Technology hand extinguisher, all results could be correlated to the mass and mass of agent flow rate used. This device extinguished a significantly higher percentage of fires than would be expected, based on its mass/mass flow rate characteristics.

Limited testing was carried out with six Halon replacements: FM-200, FE-25, CEA-4.10, CEA-6.14, FE-36 and CF_3I, using apparatus designed to give a constant discharge time (10±1 s). The results obtained appeared to be similar to Halon 1211 (50±5% extinguishment), provided the quantity of agent is scaled according to its n-heptane cupburner concentration. The two exceptions are agents with markedly different volatilities to Halon 1211 (b.p. -4°C): FE-25, b.p. -49°C, (65% extinguishment) and CEA-6.14, b.p. +58°C (35% extinguishment).

Implications for the size and weight of a hand extinguisher, based on the results of these tests, are for the physically acting agents, a weight penalty of 1.4 to 2.6, and a volume penalty of 1.9 to 2.9. If CF_3I is considered, there is a weight penalty of 1.06, and no volume penalty. However, it should be borne in mind that any hand extinguisher, before it is evaluated against hidden fires, will have had to have passed the traditional ratings (currently UL 5B:C, BS 3A:34B) to be approved for aviation use. This work is detailed in reference 4.

The International Halon Replacement Working Group has a number of sub groups each addressing a particular task. One sub group has been developing the Minimum Performance Criteria for hand held portable extinguishers. The most recent draft of this document follows.

DRAFT MINIMUM PERFORMANCE CRITERIA FOR REPLACEMENT HAND HELD PORTABLE EXTINGUISHERS FOR AIRCRAFT CABIN FIRE PROTECTION

Purpose

To establish minimum performance requirements for an environmentally acceptable replacement for the current Halon 1211 hand held fire extinguishers.

Background

FAR/JAR 25.851 require that Halon 1211 or equivalent hand held extinguishers to be installed on transport category aircraft. The regulation states that the type and quantity of extinguishing agent (if other than Halon 1211) must be appropriate for the kind of fires likely to occur where used.

These regulations had their origins with enhancing in-flight fire fighting capability including the need to deal with the arsonist/high-jacking threat which was prevalent in the 1970s. The FAA Technical Centre identified that Halon 1211 was vastly superior to the previously used CO_2 and dry chemical extinguishers, and in particular for protecting against flammable fluid fires on typical seat materials (DOT/FAA/CT-87/111). Later it was determined that Halon 1211 in handheld extinguishers, while primarily a streaming agent provided an additional benefit by having capacity to fight "hidden" fires through total flood effect. This was demonstrated on an in flight cheek space fire in a large cabin aircraft which might otherwise have resulted in a major catastrophe.

It is agreed that any replacement extinguisher must offer at least an equivalent level of fire fighting capability to the hand held fire extinguishers currently in service.

Agent Selection Guidelines

Types of Fire

The agent must be suitable for fire suppression needs typically encountered in transport and commuter type aircraft cabins, lavatories, accessible baggage compartments and flight decks.

Environmental Effect

Airworthiness Requirements specifically call for the provision of halon based portable fire extinguishers for in-flight fire fighting. For all practical purposes production of halons has ceased under the provisions of the Montreal Protocol. The primary environmental characteristics to be considered in assessing a new agent are Ozone Depletion Potential (ODP), Global Warning Potential (GWP), and Atmospheric Lifetime. The agent selected should have environmental characteristics in harmony with International laws and agreements, as well as applicable local laws. This Minimum Performance Specification sets out means of assessing the technical performance of potential alternatives, but in selecting a new agent it should be borne in mind that an agent which does not have a zero or near zero ODP, and the lowest practical GWP and Atmospheric Lifetime, may have problems of international availability and commercial longevity.

Toxicology

As a general rule the agent must not pose an unacceptable health hazard for those likely to be exposed to the agent repeatedly such as workers during installation and maintenance of the extinguishing system. In confined areas such as the cockpit or galley at no time should the agent concentration present an unacceptable health hazard whether as a result of deliberate discharge or leakage. Following release in fire extinguishment, the cumulative toxicological effect of the agent, its pyrolytic breakdown products and the by-products of combustion must not pose an unacceptable health hazard.

Performance Criteria for Fire Extinguishers and Agent

General

The extinguisher must be approved by a recognised fire testing laboratory which is acceptable to the Regulatory Authorities. Extinguishers with overall mass 6 kg or less shall be intended to be carried and used with one hand. The extinguishing agent must not present an unacceptable hazard such as serious impairment to visibility

Minimum Rating

Each extinguisher employed must contain an agent with Class A fire extinguishing capability and meet the minimum rating.
UL 5B:C or,
BS 5423 3A:34B or,
equivalent.

Hidden Fire Demonstration: (see Appendix I)

The extinguisher must meet the minimum performance standard of the hidden/remote fire challenge test.

Arson / High-jacking Threat Protection Demonstration: (see Appendix II)

The extinguisher must meet the minimum performance standard of the aircraft Arson/High-jacking Threat fire challenge test.

Compatibility with Aircraft Operating Environment

Each extinguisher utilised on the aircraft must satisfactorily demonstrate compatibility with the appropriate aircraft operational environments.

The extinguisher including its method of attachment in the aircraft must meet the following paragraphs of RTCA / DO 160C:

Section 4:	Temperature and Altitude
Section 6:	Humidity
Section 7:	Operational Shocks and Crash Safety
Section 8:	Vibration
Section 15:	Magnetic Effect

Appendix I: Proposed Hidden Fire Demonstration

A1.1 Test Fixture

The test fixture shall be 2 ± 0.050 m high, 2 ± 0.050 m long and 0.5 ± 0.025 m wide, fabricated from 0.9 ± 0.1 mm sheet steel, as shown in Figure 5. The temperature within the test fixture shall be maintained at 21 ± 1°C (70 ± 2°F). The agent shall be introduced through a hole positioned centrally in one of the end walls of the test chamber. The internal baffles shall comprise 33% hole area, and shall occupy the upper half of the test fixture, adjacent to the end wall through which the agent is injected. The baffle plates shall extend to the side walls and the roof. The spacing between the baffle plates shall be not less than 0.300 mm and not more than 0.350 m (refer to Figure 5). The solid 'stop' plates shall be 0.300 ± 0.025 m, centrally aligned with the agent injection point. Transparent plastic windows will be placed either at one end, or along one side of the test fixture to allow observation (or preferably video recording) of fire extinction times.

A1.2 Fire Threats

The *n*-heptane fire cups shall be 35 ± 2 mm in diameter, and are positioned in two arrays of four as shown in Figure 5. The fire cups shall be charged with 5 ± 1 mL *n*-heptane, floated on 10 ± 2 mL water so that the depth of the liquid surface below the rim of the cup is xxx mm. The trays for the paper fires shall be made from the same perforated material as the baffle plates, and shall be 80 ± 5 mm in diameter, 60 ± 5 mm deep. The fire load shall be 8 ± 0.1 g shredded white 80 g.s.m. copier paper, dosed with 1 ± 0.1 mL *n*-heptane to aid ignition.

A1.3 Test Procedure

The extinguisher is charged with the agent then equilibrated at 25 °C for a minimum of 15 minutes in a temperature controlled water bath. The fires are positioned in the correct zones, charged with water and *n*-heptane and ignited. Any access doors or windows are closed at this time. A pre-burn of 60 seconds is allowed, after which the agent is discharged. The discharge time and the fire extinction times shall be noted. Any fires remaining alight 60 seconds after discharge are classed as failed suppressions, and are to be extinguished manually. The chamber should then be thoroughly vented to remove both the acrid decomposition products and traces of agent which might otherwise affect the outcome of the following test. A suggested test matrix is outlined below

Test No	Fires in Locations
1	A & B
2	A & B
3	B & C
4	B & C
5	A & D
6	A & D
7	C & E
8	C & E
9	D & E
10	D & E

Thus each location is tested four times, in two different configurations.

A1.4 Presentation of Results

For each fire location the aggregate number of successful and failed suppressions shall be plotted in a figure similar to 3.2. The overall percentage extinguishment for *n*-heptane fires shall be calculated and compared to the minimum performance standard, which is yet to be defined.

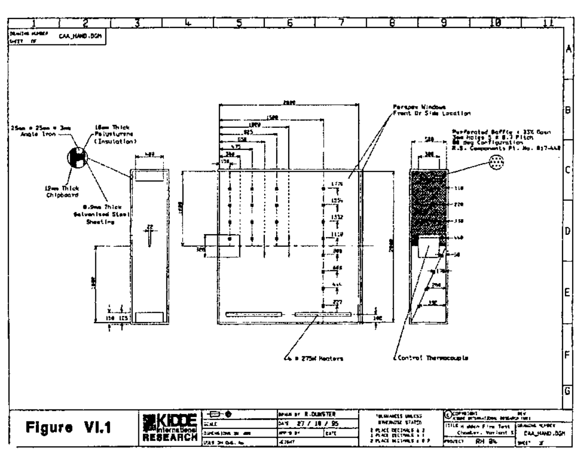

Figure 5 Construction Details of the Test Fixture

Appendix II: Proposed Arson/Hijacking Threat Protection Demonstration

Input from FAA Technical Center required.

Suggest 1 litre of gasoline spread on a triple seat, 1/3 seat backs, 1/3 top of seat cushions, 1/3 under the seat on the floor. The idea being to generate a 3 dimensional fire in a manner that could readily occur.

SUMMARY

This example of handheld extinguishers demonstrates the process of identification of key performance criteria and the development of aviation specific tests to ensure the continued high level of safety that we enjoy with the use of halon. A similar process is underway for uses such as the protection of engines and cargo compartments where Halon 1301 is the preferred agent.

The aviation business is truly international and the Aviation Authorities are striving to achieve common requirements for the design, build, operation and maintenance of aircraft. A manufacturer producing a new design can expect that decisions made in the design stage of a new aircraft type will affect the day to day operation of that aircraft type in 40 or more years time. Clearly the manufacturer will want to be absolutely sure before they commit to a new fire control system. They need to know what environmental legislation controlling CFCs, HCFCs and other alternative agents is proposed. The current differences that are emerging between the US and European environmental legislation do not help the aviation industry achieve common international safety standards. Newer concerns, beyond ozone depletion, such as global warming potential or atmospheric lifetime may be the subject of future environmental legislation which would affect agent choice.

It should be remembered that whilst the aviation industry relies heavily on halon it is not a major consumer, on average ½ kg per aircraft per year is released. The Aviation Authorities have commenced a major research effort so that they will be able to approve alternative fire suppression systems as they are developed by Industry and ensure that they are at least of equal safety to current systems which use halon.

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DISCUSSION - PAPER NO. 15

C.A. Kirk (Question)

Will the use of CF_3I handheld extinguishers be allowable in the cabin, from a toxicity point of view in the case of accidental discharge?

N.J. Povey - Author/Speaker (Response)

Both the airworthiness requirements and the draft minimum performance standard for handheld extinguishers, being developed by the International Halon Replacement Working Group, require the applicant to minimise the hazard to occupants from accidental discharge. This will apply equally to all agents considered. To make judgement, the toxicity, size of extinguisher and volume of the compartment will, at least, all need to be known.

Description and Status of Civil Aviation's Halon Replacement Program

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1. SUMMARY

Civil aviation has a major program to replace halons with environmentally acceptable agents/systems in transport aircraft fire extinguishing systems. The program is international in participation and is harmonized amongst the regulatory authorities in the U.S., Europe and Canada. An International Halon Replacement Working Group provides for frequent review and critique of progress, task group studies of issues that arise and planning of technical test activities. The program emphasizes full-scale fire tests to evaluate the effectiveness of replacement/alternative agents and to develop certification criteria for those agents that are equivalent to halon in firefighting effectiveness and are compatible with operational requirements. This will ensure that the current level of fire safety will continue to be maintained in future aircraft fire extinguishing systems.

2. INTRODUCTION

On January 1, 1994, the production of Halon 1211 and Halon 1301 ceased in the developed countries as required by an international agreement known as the Montreal Protocol. The production of those Halons was banned because they are chemicals that have been shown to deplete the stratospheric ozone layer. Recent amendments to the Protocol suggest that those agents may soon be banned from use with a mandate for their destruction. This poses a rather large problem in the aviaiton industry. The primary fire suppressing agent used on-board commercial aircraft in total flood systems is Halon 1301. Halon 1211 is required in portable extinguishers for use against passenger cabin fires.

3. HALON USE IN AIRCRAFT

Fire extinguishing systems and fire extinguishers are employed in civil transport aircraft to safeguard against an uncontrollable in-flight fire. Although the incidence of fatal in-flight fires is rare, the consequences can be great in terms of lives lost. For example, in 1980, a fire originating in the aft cargo compartment of a Saudia L-1011 spread into the passenger cabin, causing 301 fatalities in commercial aviation's worst in-flight fire accident. There was no fire extinguishing system in the cargo compartment. More recently, the ValuJet DC-9 fatal in-flight on May 11, 1996 illustrated the vulnerability of a commercial transport to unusually severe fire conditions, in this case created by the shipment of hazardous materials.

Most cabin in-flight fire and smoke incidents are controlled by the aircraft crew usually without passengers being aware of any problem. In the United States, the frequency of these reported minor fire/smoke incidents is approximately two events per week. Crewmembers are able to quickly identify the fire/smoke source (e.g., overheated lighting ballast, galley fire, etc.) and eliminate the problem. Of greater concern, however, are those fire sources which originate in hidden or inaccessible cabin areas, or vulnerable areas such as cargo compartments and engines. To protect these areas, an active fire detection and/or extinguishing system is required. The extinguishing system is designed to either extinguish the fire or suppress the fire until the aircraft can be safely landed. In the latter case, protection of aircraft crewmembers and passengers as well as critical flight systems must be assured.

Contemporary transport aircraft employ fire extinguishing agents in four applications: cargo compartments, engines and auxiliary power units, lavatory trash receptacles and hand-held extinguishers. The operational and ambient conditions and fire threats are very different in each application. In an engine nacelle, high velocity air at relatively low temperature tends to render most agents ineffective because of their low volatility and poor dispersal characteristics. On the other hand, cargo compartment agent selection is based on initial flame extinguishment and sustained inerting of the entire compartment volume for lengthy periods of time, as long as 3 hours on a transoceanic flight.

The agent of choice in total flooding applications - cargo compartment, engine nacelle and lavatory trash receptacles - is Halon 1301 ($CBrF_3$). This remarkable agent is effective over a wide range of operational and ambient conditions, and against various probable fire threats, which exist in these applications areas. Other important selection considerations include effectiveness per unit weight, low toxicity, low corrosivity and virtually no clean-up. The aviation authorities also require a minimum of two hand-held extinguishers employing the streaming agent Halon 1211 ($CBrClF_2$). Although the requirement was initially based on fuel-drenched seat fire extinguishing effectiveness, other important considerations for hand-held extinguishers include low bottle weight, hidden fire extinguishing

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

effectiveness and relatively low toxicity. An illustration of the relative quantities (pounds) of halon required in the four application areas is provided below for the B-777:

Cargo compartments	270
Engines and APU	70
Lavatories	3.5
Hand-held extinguishers	15

4. HALON REPLACEMENT PROGRAM

The halon replacement program for transport aircraft is based on the research program outlined by the Federal Aviation Administration (FAA) in 1993 (ref. 1). Although initially proposed by FAA, this is an international program with active participation by the aviation industry and the regulatory authorities in Europe and Canada, provided in large part through the International Halon Replacement Working Group, as discussed later.

The objective of the technical program is to develop certification criteria for approval of non-halon extinguishing agents and systems by the regulatory authorities in the aforementioned application areas. New agents/system must exhibit equivalent fire extinguishing/suppression performance to the currently used halons in order to maintain the excellent record of in-flight fire safety.

The major tasks of the program are as follows:

- Develop Full-Scale Fire Test Articles
- Conduct Full-Scale Evaluation Tests
- Develop Minimum Acceptable Levels of Performance
- Develop Standard Performance Tests
- Develop and Issue Certification Acceptance Criteria

In summary, full-scale test articles are developed in each application area to realistically simulate the operational and ambient environment, and fire scenarios, against which to evaluate agent performance. Selection of fire scenarios is critical in the determination of agent effectiveness, and is based on past and future likely fire loads (involved materials), including those posing a serious threat to flight systems and aircraft occupants. Full-scale tests will identify quantities of agent required to extinguish/suppress each fire condition, at the experimental discharge conditions, as well as those agents which are proven ineffective. Moreover, full-scale test data will guide the development of standard performance tests, if applicable, and will provide the primary basis for the development of certification acceptance criteria.

The technical program is guided by the International Halon Replacement Working Group (IHRWG), which since its inception in October 1993, meets three times per year in North America or Europe. The IHRWG provides for input and participation by the aviation industry and coordination and harmonization of the technical program amongst the regulatory authorities. Membership includes aircraft manufacturers, airlines, regulatory authorities, agent suppliers, extinguishing system manufacturers, the military and research organizations (government and private sector). A typical meeting will be attended by 50-75 people; however, the mailing list for distribution of meeting minutes and other information has over 400 names.

An important function of the IHRWG is the creation of task group to address issues or concerns raised during the conduct of the program. Task group memberships includes individuals with the expertise or capabilities to perform the assigned task. To date, 19 task groups have been created in less than three years to work on topics such as agent toxicity, user preferred extinguishing agents, detector service performance, etc. Perhaps, the most important task groups are those developing minimum acceptable levels of performance for each of the four application areas, an ongoing process. As discussed later, task group findings, in some cases, have been published as technical reports in order to document and disseminate results. Thus, the IHRWG is in a true sense a working group, generating needed information and guiding the direction of the technical program. One of the initial task groups formed was given the assignment of conducting a review of agents options to halon. The task group prepared an extensive report which contains a summary of available fire suppression agents, their properties and applicability in the various aircraft applications (ref.2). The relatively new halocarbon replacement agents as well as classical alternatives, including recent developments such as water mist and gas generators, are discussed in the report. Classes of agents, with presently available agents listed, were recommended for use in the development of test protocols.

5. LAVATORY TRASH RECEPTACLES

Lavatories have been the source of several fatal in-flight fires (Varig, 1973; Air Canada, 1983) accounting for 146 fire fatalities. Serious uncontrolled lavatory fires continue to occur. In 1993 an in-flight fire in the lavatory of a Dominicana 727 spread out of control and destroyed the aircraft. Also, in 1995 an International Airlines DC9 was gutted by a lavatory fire while parked at a ramp. Past fatal lavatory fires and recent serious incidents highlight the need for maintaining, if not improving, lavatory fire protection.

Lavatories present a fire safety design challenge because of four factors: (1) the existence of a variety of hidden potential ignition sources, (2) reported incidents of improper passenger activity (smoking, detector tampering, etc), (3) high ventilation rates that may mask early detection and kindle a fire, and (4) long periods when the lavatory may remain unoccupied. In the past, a source of lavatory fires has been the trash receptacle, which was the probable cause of the Varig accident that caused 123 fire fatalities. To counteract this fire threat, a built-in fire extinguisher is required to discharge automatically into the receptacle upon the occurrence of a fire. These extinguishers employ Halon 1301 and are often called "potty bottles".

Two task groups were formed to assist in the development of a halon replacement performance standard for lavatory trash receptacles. The task group entitled User Preferred Fire Suppression Agent for Lavatory Trash Container Fire Protection conducted a survey to determine airline preference for lavatory extinguisher replacement agents. A second task group was assigned responsibility for developing and recommending a standard test protocol for automatic lavatory trash receptacle extinguishers.

The survey study indicated that 83% of the airline respondents stated a preference when given the choice between halocarbon and blends (gaseous agents) and water and water based agents. That preference was gaseous halocarbon over water by a factor of 4:1. Factors such as effectiveness, "drop-in" compatibility and zero cleanup/damage were stated considerations. Nevertheless, the task group recommended that the minimum quantity of water to achieve extinguishment should be determined to better define a water based system. A report documenting the user survey was issued (ref. 3).

The test protocol task group has developed a standard test device and is in the final stages of defining the test procedure. As with any fire test standard, it is mandatory that test data generated by different laboratories be in agreement (test reproducibility). Much of the development focused on correcting the variability of the fire load, such as simplifying the type of combustibles used (paper towels only), towel conditioning and how to consistently load the containers with crumpled towels. The remaining items being finalized are the agent temperature, a parameter that dictates agent/system feasibility, and ignitor temperature measurement. It is expected that the minimum performance standard for lavatory extinguishers, which is mainly comprised of the test protocol, will be completed by the end of 1996.

6. HAND-HELD EXTINGUISHERS

In order to prevent small cabin fires from becoming a problem, the regulatory authorities require that hand-held extinguishers be conveniently located throughout the cabin. The number of required extinguishers is dictated by the passenger capacity of the airplane. Moreover, at least two of the extinguishers on an airplane with a seating capacity greater than 61 must contain Halon 1211. This requirement is based on the demonstrated superior effectiveness of Halon 1211 in extinguishing a gasoline-soaked seat fire (so called "hijacker scenario"), as compared to "classical" extinguishing agents such as water, dry chemical and carbon dioxide.

Hand-held extinguishers are employed relatively frequently to combat passenger cabin fires. In the Unites States, each year more than 100 halon hand-held extinguishers are discharged against in-flight fires; i.e., a halon extinguisher is used on the average every 3-4 days. However, the mot telling example of the value of halon extinguishers was an in-flight fire which occurred on a trans-Atlantic Delta L-1011 flight on March 17, 1991. In this incident, Halon extinguishers were blindly discharged into air return grilles, successfully extinguishing a severe electrical fire that had spread into the cabin, and likely saving the airplane and its 231 occupants.

Replacement agents for halons must be effective against typical cabin fires, including electrical and flammable liquid cabin fires, as well as the more severe fires discussed above that present a greater threat to the airplane. In addition, the following requirements must be met:

- Acceptable toxicity to occupants when discharged in cabin
- No visual obscuration particularly when used in cockpit
- Listed and rated by a recognized approval laboratory such as Underwriter Laboratories
- Size and weight that allows effective usage by a typical flight attendant

There are three outstanding tasks that need to be completed in order to evaluate halon replacement/alternative agents and develop minimum performance standards for hand-held extinguishers:

- Gasoline-soaked seat fire test standard
- Hidden fire test standard
- Agent toxicity

A standard seat fire test is required to demonstrate equivalent extinguishment capability to Halon 1211 for the hijacker scenario. This relatively simple test method will be comprised of a prescribed seat(s) with given geometry and representative, available cushion materials, and a fixed quantity of spilled gasoline. The quantity of gasoline and/or preburn time will be determined so as to barely allow the fire to be extinguished with the smallest recommended Halon 1211 extinguisher (2.5 pounds). The test will be standardized to assure that test results are repeatable within a laboratory and reproducible between laboratories. Candidate agents will be tested to determine whether or under what conditions (agent quantity, discharge characteristics, etc.) they are equivalent to Halon 2111. This task has recently been undertaken by FAA.

A test method has recently been developed for evaluating the performance of hand-held extinguishers against hidden fires, such as the aforementioned L-1011 fire that was extinguished with Halon 1211 (ref. 4). The research and development effort was commissioned by the Civil Aviation Authority in the United Kingdom and conducted by Kidde International Research. The test method simulates hidden fires such as those that can occur below the floor in the cheek area and in the cabin behind sidewall panels. This is accomplished in a box-like device, incorporating perforated panels and stop plates to simulate airframe ribs and clutter, and using 20 pan fire locations in order to extinguish a fire. Some additional work remains to be done, most notably deriving pass/fail criteria and standardizing the test procedure.

The toxicity issue is being addressed in concert with the standard seat fire test development since this severe fire scenario represents an upper bound of agent discharge quantities and cabin exposure levels. Of concern is that crew members operating the extinguishers or passengers near the discharge location are not subjected to harmful levels of the virgin agent or its decomposition products. Tests will be conducted inside a full-scale passenger cabin to determine agent toxicity during extinguishment of the standard seat fire. Toxicity will be determined from analysis of virgin agent and agent decomposition concentration-time profiles, and animal assay, if deemed appropriate. Those agents which are capable of extinguishing a standard seat fire but create harmful concentrations of agent or agent decomposition products will be rejected.

7. CARGO COMPARTMENTS

Cargo compartments in passenger aircraft present a severe potential fire threat because of the large variety and quantity of combustibles found in luggage, cargo and mail, including hazardous materials. The worst single aircraft fire accident in aviation history (Saudia L-1011, 1980, 301 fatalities) was caused by a cargo fire. The recent ValuJet accident gives evidence of the dangers associated with hazardous materials transport in cargo compartments. Fire protection in large cargo compartments is provided by a built-in fire suppression system mandated by the regulatory authorities.

Currently, all aircraft cargo compartment fire suppression systems employ Halon 1301. This total flooding agent has the capability of rapidly dispersing throughout a cargo compartment and achieving an extinguishing concentration. Moreover, systems employing Halon 1301 are designed to suppress a lingering deep-seated fire for long periods of time, 180 minutes in transoceanic flights. Related fire protection requirements imposed by the regulatory authorities include rapid fire detection (one minute), prevention of hazardous quantities of combustion products or extinguishing agent from accumulating in occupied compartments, and usage of burnthrough resistant cargo liners.

Cargo compartment fire suppression agents must also be compatible with airline operational considerations, as follows:

- Noncorrosive to cargo compartment construction materials
- Minimal residue and cleanup needs
- Non-toxic to animals that may be carried
- Low weight

Selection of replacement and alternative agent for evaluation under full-scale fire test conditions is dictated by the IHRWG and a survey of user preferred agents. The latter was a questionnaire sent to airlines throughout the world. The results indicated that a majority of airlines favor halocarbons as replacements for halon, but a significant number selected water and particulate aerosols (ref. 5).

Development of a minimum performance standard for cargo compartments by the IHRWG has focused primarily on the full-scale fire test methodology. Four critical fire threats have been identified for evaluation of replacement/alternative agents:

- Cargo container fire
- Bulk loaded luggage fire
- Surface burning fire
- Aerosol can/luggage fire

Additional test parameters, such as compartment volume and fire load (percentage of compartment volume occupied by cargo) add to the extensiveness of the required testing. Halocarbons, water and particulate aerosols have been tested under selected fire threats and test parameters, as discussed below, to determine their effectiveness against cargo compartment fires.

FAA employs two wide-body cargo compartment test articles for agent evaluation. The cargo compartment and cabin section of the test article are extensively instrumented to measure temperature, smoke levels, and gas concentrations, including agent, agent acid gas decomposition products, oxygen, carbon dioxide and carbon monoxide. Two halocarbon agents, HFC-125 and HFC-227ea, have been evaluated against surface burning and bulk-loaded luggage fires. Both agents required considerably higher quantities than Halon 1301 to achieve fire suppression. Moreover, for the deep-seated fire created by bulk-loaded luggage, the agent quantities for fire suppression were 30-40% higher than laboratory (cup burner) measurements, thus reinforcing the importance of full-scale fire tests for evaluation of agents. Another finding which is of concern is the unusually high measured concentrations of acid gases in the cargo compartment caused by halocarbon agent decomposition. The acid gas concentrations are significantly higher than measured with Halon 1301. The next step is to examine the remaining fire threats and add triodide (CF_3I) to the halocarbons evaluation. In order to test triodide; gas analysis techniques are being developed to measure iodine containing decomposition products.

FAA also conducted a preliminary evaluation of pyrotechnically generated aerosols. It was necessary to devise a system that discharged every seven minutes in order to adequately counter agent concentration decay. Based on the preliminary tests, it was concluded that the generators require cooling, and a better system was needed for discharging to the initial extinguishing concentration and sustaining an inerting concentration. These findings, as well as possible corrosion and toxicity issues, and the need for cleanup in the event of an inadvertent discharge, has discouraged further testing of pyrotechnically generated aerosols.

Dual fluid and high pressure (fog) zoned water spray systems have been tested by FAA. Water spray is slowly receiving more consideration as a potentially viable halon alternative. There are not environmental, toxicity or supply concerns, and a cargo compartment system may make a cabin system cost effective (cabin water spray is highly effective improving postcrash fire survivability). On the negative side are concerns associated with an inadvertent discharge, preventing freezing and weight penalty.

At this time, the high pressure system requires the least amount of water. Deep-sealed fires inside a cargo container, believed to be the worst case fire threat for a water-based system, were effectively suppressed for 90 minutes by utilizing 30-35 gallons of water. This "optimal" quantity was determined by trial and error, varying certain spray parameters. A deep-seated, bulk-loaded luggage fire was suppressed with only 25 gallons of water. In both cases, although the system contained eight zones, only a single zone, encompassing the fire location, activated over the test duration. Further optimization of the system to reduce the required water quantity to about 15 gallons would make water spray competitive with Halon 1301 on an equivalent weight basis.

In Europe, a major water spray R&D program was recently initiated by a consortium of organizations which includes the CAA. Cargo compartment water spray fire suppression tests will be conducted utilizing the fire test methodology and fire threats outlined in the draft minimum performance standard. The primary emphasis is on the development and validation of a water spray/fire suppression computer model.

8. ENGINE NACELLES and AUXILIARY POWER UNITS

The regulatory authorities require engine and auxiliary power unit (APU) compartment fire extinguishing systems. The current fire extinguishing systems use Halon 1301 as the fire extinguishing agent. Usually, compliance with the regulations is based on a performance test, demonstrating the ability of the system to deliver and maintain gas concentrations at specified levels. In the case of Halon 1301, the requirement is 6% concentration throughout the protected fire zone for a duration of 0.5 second. With halocarbon replacement agents other criteria will apply. However, with non-gaseous alternative agents, a totally different means of compliance may be required.

One of the primary factors leading to the selection of Halon 1301 in aircraft fire extinguishing systems is its effectiveness over a wide range of operational conditions. This is especially true for the engine/APU application, since a fire may occur during any phase of the flight regime. The agent is discharged rapidly and expands throughout the engine nacelle in order to be able to extinguish any likely fire. All of this must occur in a matter of seconds, before the high speed air flow flushes the agent away. Cold ambient temperatures leads to the selection of volatile, low boiling point agents. Engine fires which can become very intense at flight speeds are a great concern because of the large quantities of fuel supplied to the engine and the proximity of the engine to the fuel tanks or fuselage. Therefore, it is imperative that engine fires are rapidly extinguished and controlled.

Construction of an engine nacelle test article by FAA, which will be capable of evaluating the fire extinguishing effectiveness of replacement agents for equivalency to Halon 1301, is near completion. Testing is expected to commence before the end of 1996. The IHRWG has defined the design of the test article, specified critical test parameters and conditions, and prioritized the evaluation of replacement agents.

Prioritization of agent evaluation was accomplished by a written survey of airlines and engine, APU, and aircraft manufacturers around the world (ref. 6). Based on the survey, the initial replacement agents tested will be FIC-13I1 (CF_3I) and HFC-227ea (C_3HF_7). This will be followed by HFC-125 (C_2HF_5), an agent extensively tested and selected for future aircraft by the U.S. Air Force. Upon completion of evaluation of the above three halocarbon gases, gas generator technology will be examined. The end users selection of agents for evaluation reflect two unique engine fire extinguishing system considerations. First, the ability of gaseous agents to operative effectively in a low temperature, high air speed environment. Second, concerns with new agent systems that would require larger storage/plumbing space in an already space-limited environment, emphasizing the preference for a "drop-in" replacement.

A draft minimum performance standard for engine/APU fire extinguishing systems specifies the requirements for replacement agents/systems and the test apparatus and methods for evaluating agents/systems. The latter is detailed in the draft standard, reflecting the many parameters that must be examined and the harsh engine environment, as illustrated below. At least two internal airflow rates are required, with the high rate equivalent to about one air change per <u>second</u>. Temperature extremes must be examined; i.e., air temperatures of 100°F and 400°F, engine casing temperatures of 900-1200 °F and agent storage temperatures of -65°F and 200°F. Simulated blockage or clutter must reduce the local cross section by 50%.

The draft standard describes the types of fires that must be developed for agent evaluation. The fires must be "robust", i.e., capable of being extinguished by a Halon 1301 system compliant with current certification criteria, but not always (a robust fire will be extinguished in 70-90% of repeated fire tests.) Two general types of fires must be employed: a flaring fire (leaking fuel stream on fire, also called a spray fire) and a residual fire (baffle stabilized pan fire due to ignition of accumulated fuel in some part of the fire zone). Three different combustible fluids for the fire must also be considered: aviation engine fuel, hydraulic fluid and engine oil.

The IHRWG has defined an extensive fire test program to evaluate engine/APU halon replacement fire extinguishing agents/systems. The development of engine fire test articles simulating modern engine/APU compartment operating conditions and probable fires in designated fire zones is necessary because the genesis of current halon extinguishing agent certification criteria is testing conducted in the 1950's and 1960's. The key is to determine halon replacement agent quantities and concentrations that will extinguish engine/APU robust fires over the wide range of current powerplant operating conditions.

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DISCUSSION - PAPER NO. 16

E. Schwartz (Question)

1) What is the timetable/schedule for the FAA to develop certification standards for fire extinguishing agents?

2) In the meantime, what can manufacturers do to move towards 'Halon-free' aircraft?

R.G. Hill - Author/Speaker (Response)

1) The up-to-date timetable for the Halon Replacement program of the FAA is available through the International Halon Replacement Working Group, by request (FAX number USA: 609-646-5229).

2) The Authorities are only developing acceptance criteria. It is the manufacturers' responsibility to develop replacement agents and systems.

Performance of fire fighting powders

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1. SUMMARY

A series of dry powder fire extinguishing tests have been carried out by Faverdale Technology Centre for the Civil Aviation Authority's Safety Regulation Group.

The aim of the test programme was to design a test specific to those aviation fuel fires which are not covered by normal class 'B' fire testing. It would then be possible to assess objectively the performance of dry powders for aviation uses.

A specially designed test rig on which the fire tests would be carried out was designed and developed to model a running fuel fire and spray fire. The test method involved the manual application of the dry powder by personnel trained in the art of firefighting.

The test programme was split into three phases:
Phase A - set out to determine the suitability of Monnex® dry powder as a benchmark for future tests by extinguishing fires of Jet A1 aviation fuel within a 0.66m² pool tray.
Phase B - concentrated upon small scale testing on a 2.8m² pool tray, using Monnex® and a standard powder.
Phase C - comprised of an investigation into the optimum mass of dry powder required to extinguish two different full scale fire test scenarios; that is a cascade fire and the spray fire. Three different types of dry powder were employed, one Monnex® and two standard powders.

All the tests were instrumented with metal sheathed thermocouples and heat flux meters to monitor the fire characteristics of temperature and radiant and convective heat flux respectively.

The fire test methods used are described and the performance of the dry powders are presented in this paper. The results from the Monnex® tests are compared with the results from the standard powder tests. Particular attention was paid to the mass of powder required to extinguish each test fire.

Although two different standard powders were used, only one of these was particularly suited to class B fires, hence the performance of this other powder was seen to be totally ineffective against any of the fuel fires it was tested on.

The other standard powder was suitable for class B fires and the average mass used to extinguish the spray and cascade fires was more than the average mass of Monnex® required for the same fires.

In summary Monnex® used less powder to extinguish the Phase B and C fires and was therefore considered to be a suitable agent to be used as a benchmark for further tests.

This work is not conclusive and current investigations are studying the effect of application discharge rate of Monnex®. Once these studies show the optimum application rate of Monnex®, work to compare with other dry powders will resume.

2. INTRODUCTION

The Civil Aviation Authority (CAA), through CAP 168 Licensing of Aerodromes, currently permit a 50% remission on the minimum amount of dry powder to be stored at the aerodrome if Monnex® is used. More recently, alternative dry powders have been developed and the CAA then made the decision that dispensation of the quantity of stored powder at an airfield should be determined from performance against a specifically designed test.

Although British Standards exist against which a dry powder can be tested, these are for general class B fires and concentrate upon the physical properties of powder and pool fire testing. When airport fire-fighters attend an incident, dry powder is used in stored pressure portable extinguishers typically 9kg-100kg capacity. Foam is used to contain any fuel spillage, and the powder is used for extinguishing of airborne flames as a general rule, not ground spillage fires. The aim of the specifically designed test programme was to simulate the type of fires that dry powder would be used to combat on the airfield, firstly the rupture of a fuel tank running along the aircraft wing and cascading through space to form a running pool fire and secondly the break of a high pressure fuel line with the transfer liquid being sprayed from the broken pipe. The full scale rig was designed and developed to simulate these cascade and spray fire scenarios separately.

The fuel used in all the test trials was Jet A1 aviation fuel. It was widely accepted that heptane was an unrealistic fuel to use in this testing, as it was unlikely to constitute the burning source in an aviation fire. Since Jet A1 is a common fuel used in aero turbine engines and it has comparatively safe properties, it was decided to be used as a fuel source for the test trials.

The fires were instrumented with heat flux radiometers to measure the radiant and convective heat of the fire, and thermocouples to measure the flame temperature. A data logger was then used to record the collected data every half a

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second. All tests were recorded by a video camera. Weather conditions were monitored throughout the tests, with direct measurement of windspeed and ambient temperature.

2.1 Phase A

Before testing on the full scale test rig, an introductory phase was embarked upon to determine the suitability of Monnex® as a benchmark for all future tests. This was entitled Phase A. The British Standard BS6535:PART 3:1989 and its updated draft version, PrEN 615:1991 Appendix E: Fire extinguishing performance, was used as a guidance to conducting the fifteen tests carried out in December 1994.

The tests in Phase A were carried out of doors in an open three sided shelter at Faverdale Technology Centre (FTC), Darlington.

3kg cartridge operated, hand held extinguishing units were used to dispense the powder by a manual firefighting application.

2.2 Phase B

After testing Monnex® on small scale pool fires in Phase A, the aim of the second phase of the programme was to conduct some test trials on a medium scale pool tray using Monnex® and, as a comparison a standard powder. Phase B conducted thirty four tests within the same open roofed shelter as was used in Phase A, but with only two sides to reduce the vortex effects of the wind.. The Phase B tests took place in January and February 1995.

9kg stored pressure, handheld extinguishing units (as used in practice by the aerodromes) were used to dispense the powder using a manual firefighting application technique.

2.3 Phase C

On completion of Phase B, the third phase of testing commenced with the development of the specifically designed test rig. Once satisfied that consistent, repeatable testing was being achieved, one hundred and forty tests were carried out. Due to strict repeatability, only sixty five tests were used for result purposes.

The two types of tests performed during Phase C were;

(i) SPRAY TEST: This was designed to simulate a high pressure release fuel fire. Fuel was pressure fed through four spray nozzles, pitched equal distances along the two sides of the test rig.

(ii) CASCADE TEST: This was designed to simulate a three dimensional running fuel fire. Fuel was fed at approximately 40 litres per minute through ten equally pitched holes (9mm diameter). The fuel cascaded over the fins jutting out from the side of the rig and cascaded through air to collect on a 2m by 2m base tray.

9kg stored pressure, handheld extinguishing units were used to dispense the powder using a manual firefighting application technique.

3. TEST APPARATUS AND METHODS

3.1 Test Location

All tests were performed out of doors. Tests in Phases A and B were carried out at FTC, Darlington. Tests in Phase C were conducted at the International Fire Training Centre's Fire Training Ground at Teesside International Airport, Co. Durham.

The Fire Training Ground hold a licence for release of combustion gases, hence for the full scale tests involved in Phase C this was an important factor, in choice of site. The wind speed on the site was representative of that occurring on a typical airport runway, that is, with no wind barriers - just open land.

3.2 Pool Fire Trays

The pool tray used for Phase A testing was a circular tray having the following parameters;

Diameter at rim:	920mm
Depth:	150mm
Thickness:	2.5mm
Material:	304 stainless steel

The pool tray used for Phase B was circular and had the following properties;

Diameter at rim:	1890mm
Depth:	200mm
Thickness:	2.5mm
Material:	304 stainless steel

This pool tray had several supports welded to its base to prevent any distortion occurring. The tray sat approximately 100mm from ground level.

The trays were positioned centrally within the open roofed shelter.

3.3 Fire Test Rig

This full scale rig was designed and developed for Phase C. A stainless steel 2m by 2m by 0.25m deep tray formed the base of the test rig. A hollow rectangular pillar 2m high, was welded into one corner of the base. This pillar was fitted with rectangular fins fitted at 0.25m intervals down two adjacent faces. There were seven fins on each side in total.

The pillar had ten holes (0.9mm diameter) drilled into its top section, five on each face. Fuel was stored inside the pillar on top of a water base and pumped through the holes at the rate of approximately 40 litres per minute.

The four spray nozzles were mounted on top of the pillar structure, all fed from one source. A protective stainless steel plate was fitted to the top of the rig to ensure the copper tubing did not receive too much flame heat. The nozzles were a standard angle, hollow cone type, and were fed from a pressurised line at approximately 6 bar.

Two protective shields were attached to the outer edges of the two fuel covered faces, ensuring flames did not move around the back of the rig. It was discovered during the development trials that to firefight a 360° fire with dry powder would be impossible, as the operator would be "chasing his tail" around the pillar.

3.4 Ambient Temperatures

The results section indicates the ambient temperatures under which the tests were conducted, in graphical format.

No control was made over the temperature of the fuel/water mixture in the trays.
The dry powder extinguishing units were always stored indoors until required for testing. No measure of the units' temperature was made.

3.5 Wind Speeds
The results section indicates the wind speeds measured during each of the tests, in graphical format. Obviously no control could be made over the wind speed, and some conditions made testing impossible. A limit of 10 knots (6 m/s) was imposed to ensure that representative airfield winds would be encountered. This limiting of the wind speed would improve test conditions, providing limits within which repeatable testing could take place.
After Phase A, it was concluded that effects of the wind greatly affect the burning rate of the fire, and a limit of 4 metres per second (7.8knots) was imposed.

3.6 Powder Application
The British/European draft standard does not specify a procedure for application of dry powder other than to 'apply the powder'. No criteria are given such as minimum distance for application, or attacking from a leading edge. Such criteria are very important and airport fire-fighters spend approximately 3 weeks training at a fire training school, and repeat this training every five years. The techniques taught to the students involve strategic application. These techniques were used during development trials and powder application methods were overseen by an Aerodrome Inspectorate.

Powder application was from upwind. The full scale test rig was always positioned such that the apex of the rig was directly upwind, and thereby constituted the leading edge, from which the powder was applied.

Before applying the powder, the extinguishing unit would be turned upside down to disturb the contents of the unit and after the preburn, the operator would apply the powder from a minimum distance (1 metre) from the flames. Care was taken never to agitate the flames with the powder, as this was a hindrance to the performance of the powder.

The powder was directed towards the test fire with the aim of knocking out the free radical reactions, and thereby stopping the flame's chain reaction process. In Phases A and B the powder was applied via a sweeping motion from left to right from the front of the pool tray, and once the flames were knocked down progression was made to the rear of the tray. The operator never moved around the periphery of the tray but kept in one area and used the 'throw' from the hose attached to the extinguishing unit to knock down the flames furthest away from him.

During Phase C where the fire area was larger, the operator began application from the leading edge, which as described was always the apex of the test rig. The tray fire in the bottom received the application first, with the operator sweeping from side to side covering as large an area as possible. It was necessary to step once in either direction to ensure powder reached into the two furthest corners of the tray.

Once the fire in the tray was extinguished, the powder application was concentrated upon the pillar of fire, and swept from side to side up the pillar 'mopping up' the flame until all flame had been extinguished.

3.7 Fuels
Although BS6535:Part 3:1989 specifies the use of heptane as the fuel for fire testing, it was decided that a more effective representation of a fuel spillage incident could be to use an aviation fuel commonly used in turbine engines. The Jet A1 was supplied by Conoco, table 1 details its physical properties.

Table 1: Physical properties of Jet A1

Flash point	38°C
Auto ignition temperature	248°C
Limits of flammability	0.7 to5.8%
Specific gravity	0.8
Flame spread (metres per minute)	30

Jet A1 is a kerosene based fuel used in turbine engines. To minimise the need for complex safety procedures it was decided to use Jet A1, due to its relatively high flash point of 38°C and low vapour pressure. These factors meant that four star petrol was required to 'spice' the pool and cascade fires. Jet A1 could be handled without the need for respiratory protection and breathing apparatus sets, which would have been required had a more volatile jet fuel been used for the tests. The storage facilities for this fuel were also further simplified. Approximately 0.5litres of four star petrol was added to the test trays prior to ignition, to encourage the auto ignition of Jet A1 (248°C) to be met.

The fuels were stored in the flammable liquids store at FTC for Phases A and B. Phase C fuels were stored at suitable facilities on the Fire Training Ground at Teesside.

All tests contained the Jet A1 on a water base. The water base was designed to cool the base of the tray.

Table 2: Quantities of Jet A1 used during testing

Phase	Depth water	Vol. water	Depth fuel	Vol. fuel	Fuel Flow
A	12mm	81	30mm	161	
B	30mm	851	45mm	1001	
C-Cascade					401 / min
C-Spray					0.51 / min

3.8 Preburn
During tests in Phase A, a preburn of 60 seconds (1 minute) was allowed, measured from the ignition of the entire pool tray to the start of the powder application. The guide as to this preburn time was taken from the British Standard.

Prior to Phase B, a study of the temperature and heat flux was made. This study showed that between 10 and 20 seconds after ignition of the fuel, both the temperature and heat flux readings had reached steady state conditions. It was therefore decided that a preburn of 30 seconds would be sufficient, enabling the pool tray to reach equilibrium.

Phase C - Cascade preburn was measured from when the whole base tray and pillar was burning. This could take up

to 60 seconds. Once the entire rig was on fire, a preburn of 30 seconds was allowed before commencing application of the dry powder. The Phase C - Spray fire became ignited as soon as the sprayed fuel came into contact with the propane lighting torch. Application of the powder occurred 30 seconds later. Table 3 below summarises.

Table 3: Preburn times

Phase	Preburn (seconds)
A	60
B	30
C - Cascade	30
C - Spray	30

3.9 DRY POWDER

The following powders were used:
Phase A - Monnex®
Phase B - Monnex®, BC30 and GPS
Phase C - Monnex®, BC30 and GPS

3.9.1 Monnex®

Manufactured by Croda Kerr Ltd, Liverpool. Monnex® dry powder is composed of two main chemicals, that is urea and potassium bicarbonate. It decomposes at 270°C in the flame zone and breaks down to form smaller sized particles which absorb the free radicals, stopping the flame's chain reaction.

3.9.2 BC30

This powder is also known as Centrimax BC and BC 30S. It is manufactured by Croda Kerr, Liverpool. It is composed of sodium bicarbonate and calcium carbonate compounds. It decomposes at 270°C in the flame zone.

3.9.3 GPS

GPS is manufactured by Chubb. It is an ammonium phosphate based powder. GPS is a general purpose dry powder extinguishing agent. It is suitable for class A, B and C fires. It is not designed specifically for class B fires, but as its name suggests for use generally as an extinguishing agent.

These standard powders were used to examine the effect of *different* dry powders on extinguishing the test fires. In the results section of this paper, the two standard powders are identified by the letter 'S'. No distinction between the two powders is made, since the aim of this work was to analyse the test rig and method by using powders other than Monnex®.

3.10 Fire Extinguishing Units

3.10.1 Phase A

Two types of fire extinguishing agent were used during Phase A tests; four nitrogen stored pressure and three carbon dioxide cartridge operated units each of 3kg capacity. The cartridge extinguishers were reused as necessary throughout the phase A test period. No facilities were available to recharge the stored pressure units with the nitrogen gas, hence these units were used only once. The cartridge operated units were stripped down and recharged according to the manufacturer's instructions. These new extinguishing units were supplied by Hoyles Fire and Safety Ltd. The cartridge operated unit's discharge rate was given by the manufacturer as 0.4kg per second. The stored pressure unit's discharge rate was given as 0.37kg per second.

3.10.2 Phase B and C

9kg capacity, air stored pressure extinguisher units were employed during Phase B testing. These were new units supplied by the International Fire Training Centre at Teesside Airport. The extinguishers were reused, but stripped down and serviced each time they were used.

These 9kg units had a stored pressure requirement of 10 bar. Time to discharge was specified by the manufacturer to be 15 seconds. This equates to a discharge rate of 0.6kg per second.

3.11 Instrumentation

3.11.1 Thermocouples

The temperature of the flames was measured using Inconel 600 sheathed thermocouples. The head diameter of the thermocouple was 1.5mm, which equates to a 0.3 second response time.

A calibrated handheld temperature measurement device - digitron, was used to record the ambient temperature immediately before the start of each test.

Phase A

Three thermocouples were used. They were positioned at 120° intervals around the circumference of the pool tray, at approximately 200mm in from the outer rim of the tray.

Phase B

Four thermocouples were used. They were positioned at 90° intervals around the tray's circumference, at approximately 200mm in from the outer rim of the tray.

Phase C

Two thermocouples were used, positioned centrally, approximately 400mm beneath the spray nozzles and approximately 200mm beneath the start of the cascade flow holes.

The results section shows average preburn flame test temperatures for each phase of the testing programme. Graph 1 shows pool fire temperatures, graph 2 shows cascade temperatures and graph 3 shows spray temperatures.

3.11.2 Heat Flux Radiometers

Signals from heat flux radiometers were recorded throughout the testing series. These instruments gave a measurement of the radiant and convective heat emitted by the test fire. The instruments were water cooled, Medtherm radiometers, of the Gardon Gauge type. The temperature of the water used to cool the instruments was between 5 and 15°C. The output signals from the heat flux radiometers was measured by a voltmeter accurate to 0.001mV. A datalogger programme was then used to convert the radiometer millivolt signal into heat flux readings.

Phase A

Three heat flux radiometers were originally used during Phase A tests. During the initial Phase A development

tests, high wind speeds in unsheltered conditions gave rise to a large flame spread which had an adverse effect on two of the three instruments. Unfortunately, two of the heat flux radiometers were burned out, hence only one set of readings was available for the majority of Phase A testing.

The heat flux radiometers were positioned at a height of 400mm above ground level, with the sensing face of the instrument positioned parallel to the ground. The distance between the sensing face of the radiometer and the tray edge was 1000mm. The instrument was positioned perpendicular to the direction in which the powder was being applied.

Phase B

One instrument was used during Phase B. A second instrument was introduced halfway through the testing programme. Lead times for procurement of a heat flux radiometer was a minimum of six weeks, hence the unavoidable absence of a second radiometer until test 18.

The heat flux radiometers were positioned at a height of 1000mm above ground level, with the sensing face of the instrument positioned parallel to the ground. The distance between the sensing face of the radiometer and the tray edge was 1000mm. The instrument was positioned perpendicular to the direction in which the powder was being applied.

During Phase B a separate study was embarked upon to investigate the effect of dry powder upon a radiometer signal.

Phase C

As a result of the study into the effects of dry powder on the reading of the radiometer, it was concluded that only one radiometer was required for Phase C.

The heat flux radiometer was positioned at a height of 1000mm above ground level, with the sensing face of the instrument positioned parallel to the ground. The distance between the sensing face of the radiometer and the tray edge was 2000mm. The instrument was positioned perpendicular to the direction in which the powder was being applied.

3.11.3 Datalogger

A Solatron SI 3535D datalogger was used to record the signals from the thermocouples and the heat flux radiometers. This datalogger is a multi task processing and recording device with an accuracy of 0.05%. Recording of the data occurred every 0.5 second.

During Phases A and B, mains electrical power at FTC was used to power the datalogger. Due to the remote nature of the airfield site during Phase C testing, the datalogger was powered from a battery source.

3.11.4 Anemometer

An air velocity meter (anemometer) was used to measure the windspeed during the fire tests. This instrument consisted of an "x probe" connected to a battery driven unit which gave instantaneous readings of windspeed in metres per second.

3.11.5 Scales

A purpose built stand and weighing scales unit was employed throughout the testing to measure the mass of the extinguishing units before and after each test. This device has an accuracy of +/- 0.25kg.

3.12 Timing

All timing and associated instruction to the test personnel was performed by a designated individual. It was their job to ensure that the sequence of events was performed to the specific timescales required for that test. In all phases a calibrated stopwatch was used to measure preburn, from the moment of total engulfment of the test fire. The dry powder operator would then be counted down to the second for application of powder to begin.

Actual time to extinguish the fire was not measured "live". This time was taken from the video footage of each test, studied back at the laboratory.

3.13 Video

Each test was recorded by a video camera. The camera was positioned upwind of the test fires. The test number, date and timer were generated to appear on the video tape footage, making each test identifiable for study at the laboratory.

3.14 Safety

A risk assessment was carried out prior to each phase of work. This analysis was then used to create a safety procedure which was adhered to during each test.

Particular issues that received attention were: fire fighting training for all personnel associated with the project; the wearing of appropriate protective safety clothing; and having alternative extinguishing media to cover for all fuel transfer operations.

During Phase C large quantities of fuel were being stored in reservoir tanks prior to it being pumped through to feed the spray nozzles. The design of the Phase C test rig enabled a 10 metre distance between this fuel and the test fire to be kept.

3.15 Environmental Impact

Tests carried out at Faverdale were on a small scale, both in terms of the size of the test fire and in number of tests carried out (80 tests in total during Phases A and B). Disposal of spent fuel and dry powder was made through a licensed waste disposal organisation. All spent fuel and powder residue was stored in steel drums, and at the end of the project, this waste was removed from FTC.

Testing at Teesside airport was of a much larger scale, both in terms of size of test fire and number of tests carried out (in total 170 tests were performed during Phase C). Contaminated fuel and dry powder was washed into the drainage system on the fire training ground, where a reed bed filtration unit ensured that the effluent was not washed into the mains water system.

When choosing the site on the airfield to test, it was always ensured that the fall out of dry powder would land on the site concrete, hence washing down the filtered drainage system of the fire training ground.

4 EXPERIMENTAL PROCEDURE

4.1 Preparation Phase A and B

4.1.1 Fire Extinguisher Units
The extinguishers to be used would be prepared for tests. Normally between four and eight units would be prepared at the same time, allowing this number of tests to run sequentially once testing had begun.

4.1.2 Fire Trays
The pool trays were placed in their position for testing. The trays were then cleaned out, and filled with the prescribed quantities of water and fuel.

4.1.3 Instrumentation
The thermocouples were placed in position in the trays and the heat flux radiometers placed in clamp stands. The instruments were then connected to the datalogger via a network of backleads. The signals and readings from these instruments were checked before the test proceeded.

4.1.4 Personal Briefing
Prior to each test day, the personnel carrying out the tests were briefed, to instruct them as to the aims and procedures for that day. Protective safety equipment would be issued.

4.2 Testing Procedure for Phases A and B
Once all preparation had been carried out, the following procedure was adopted for Phase A and B.

4.2. The weather conditions were recorded, that is ambient temperature and a description of the climate. No tests were carried out in the rain, since this had an adverse effects on the reading of the heat flux radiometer.

4.2.2 The propane lighting torch was ignited and left lit on standby.

4.2.3 The extinguisher to be used for the test was weighed.

4.2.4 The jet fuel was then spiced with approximately 0.5 litres of petrol and immediately lit with the propane torch.

4.2.5 The video camera was switched to record.

4.2.6 Once the whole tray was engulfed, the stopwatch was switched on to count.

4.2.7 After the preburn time had elapsed, an audible count down to time to extinguish was made, for the benefit of the operator. During the preburn period the windspeed was measured, and recorded.

4.2.8 Powder was applied until the fire was extinguished. If the fire was not extinguished the test was concluded to be a fail.

4.2.9 On the ceasing of powder application, the extinguishing unit was weighted and the mass of powder used during the test recorded.

4.2.10 To ensure there remained sufficient fuel in the tray, the fuel mixture was relit after each test to prove that it was the powder that extinguished the fire, and not suffocation due to lack of fuel.

4.3 Preparation for Phase C
4.3.1 Fire Extinguisher Units
The extinguishers to be used were prepared for tests, by the International Fire Training Centre. Sufficient quantities of extinguishers would be prepared for each half day testing.

4.3.2 Test Rig
During Phase C tests the test rig was always moved to ensure the apex of the rig was downwind, thereby providing the operator with a leading edge. Unfortunately wind direction was erratic on a couple of occasions. On these occasions the operator would initiate application from a long edge of the test rig, instead of the apex.

For the cascade fires, fuel would be poured into the top of the pillar, floating on a layer of water. For safety reasons a quantity sufficient for one test was used. For the spray fires, the reservoir tank feeding the four spray nozzles was filled with a quantity of fuel, again sufficient for one test only.

4.3.3 Instrumentation
The thermocouples were placed in position on the two sides of the test rig and the heat flux radiometer was clamped in its stand. The instruments were then connected to the datalogger via a network of backleads. The signals and readings from these instruments were always checked before the test proceeded.

4.4 Procedure for Phase C
A procedure similar to that followed during Phases A and B was undertaken, as was all measurements and recordings.

The base tray was filled to a prescribed level with water.

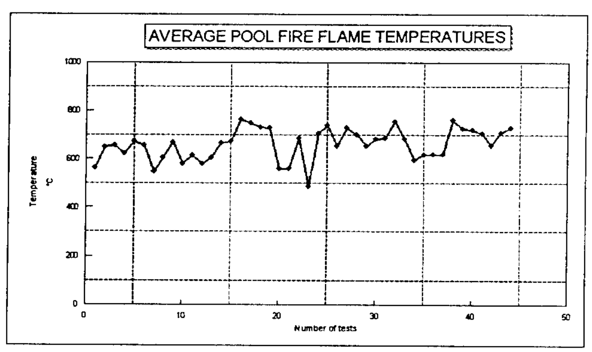
To initiate the cascade fire, the pump was switched on which caused the fluid level in the pillar to rise, thereby displacing the floating fuel through the holes, and down the fins cascading into the base tray and forming a pool.
Petrol was then added to the cascading fuel, and lit with the propane torch.

Preburn timing only began once the whole test rig was engulfed in flame.

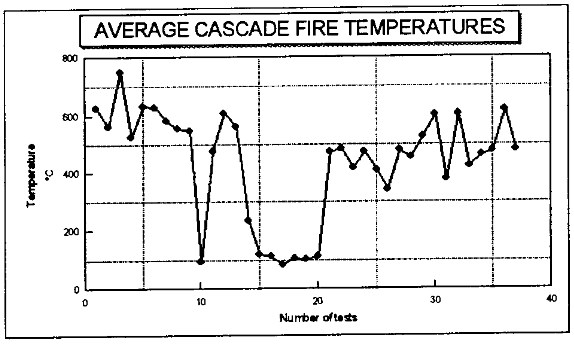
For the spray tests, the pump was switched on, and the fuel lit as soon as it emerged from the nozzles.

5 RESULTS

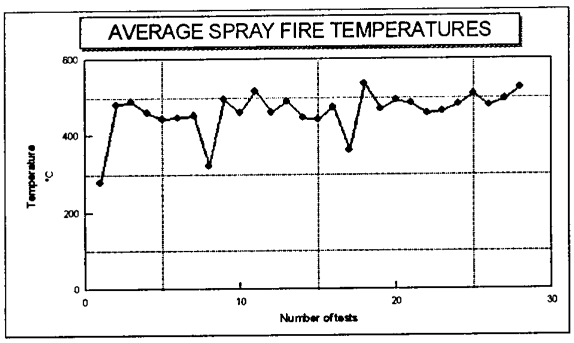
5.1 Results Graph 1



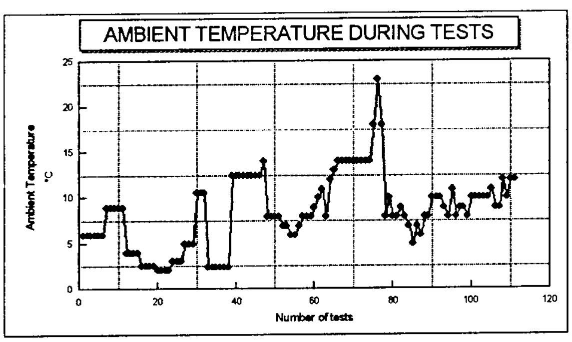
5.2 Results Graph 2



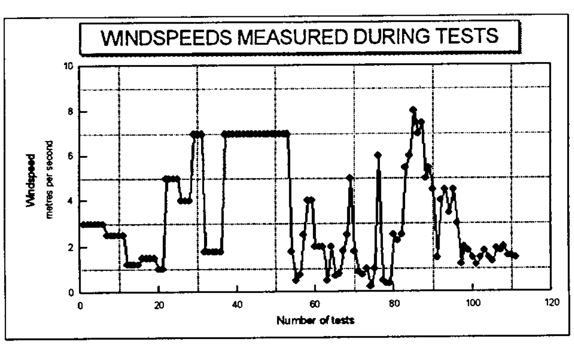
5.3 Results Graph 3



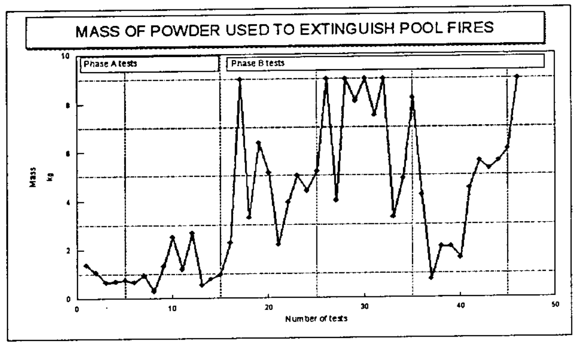
5.4 Results Graph 4



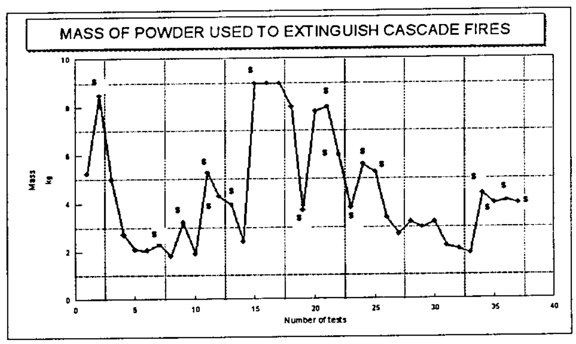
5.5 Results Graph 5



5.6 Results Graph 6



5.7 Results Graph 7



5.8 Results Graph 8

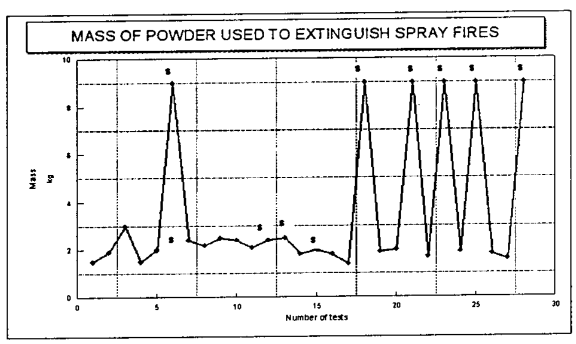


Table 4: Average mass of powder used

Phase	Type of powder	Mass
A	Monnex®	1.08kg
B	Monnex®	3.95kg
	BC30	4.52kg
C-Cascade	Monnex®	3.95kg
	BC30	4.78kg
C-Spray	Monnex®	1.94kg
	BC30	2.32kg

6. DISCUSSION AND CONCLUSION

The objective of designing a test specific to aviation fuel fires in order that an comparative assessment be made of a dry powders' performance was achieved. The test rig designed and developed in Phase C provided apparatus to carry out fire testing to the method described in this paper.

Results Graph 1 shows the average preburn temperature during the tests at FTC. These temperatures were consistent and the majority fell between 500 and 700°C.

Results Graphs 2 and 3 show the average preburn temperatures measured during the test fires performed on the airfield. The effect of the high wind speeds in these results is apparent. Measurements of high wind speed correlated with low temperature measurements. This was primarily due to the dispersion of vapours from the hot fuel, reducing the concentration of vapour required for combustion. A limit on windspeed was therefore introduced to 4 metres per second. Results Graph 5 illustrates the measured wind speeds during testing.

Results Graph 4 shows the ambient temperatures measured on the test dates. The ambient temperature is concluded to have little effect on the extinguishing performance of the powders used in this study. No control over these temperatures was made since the ultimate aim was to simulate airfield conditions, and incidents can occur at any time of the year.

Table 4 summarises the test information contained in the Results Graphs 6 to 8.

Perfect repeatability in this test programme was impossible to achieve. Parameters that were within FTC's control were ensured to be similar each time a test was carried out. That is, volume of water/fuel; preburn timing; positioning and application technique of the operator were all reproduced time and again. There were however certain parameters that were outside of FTC's control, such as windspeed, wind direction and ambient temperature. Once evaluation as to the effect of these parameters was established, limits upon these factors were introduced thereby improving testing repeatability.

Although differences between the average mass of standard powder and Monnex® required to extinguish was realised, these differences were not as great as the CAA would have expected. As a result, investigations into the critical discharge rate were embarked upon. These investigations took into consideration the effects of high wind speeds on the test programme and subsequently reduced the testing limit to 4 metres per second. Testing with the aim of studying the critical application rate of the spray and cascade fires is currently underway , and due for completion late 1996.

INTERIOR CONDITIONING IN MILITARY TRANSPORT AIRCRAFT CERTIFICATION

by
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Summary

This conference gives an overall vision of the task to be carried out regarding the Interior Conditioning System of a Military Transport Aircraft in order to obtain its Type Certificate.
The following will be analysed in more detail:
- Assessment of the certification Requirements, and their fulfilment, applicable Standards, Test facilities and associated problems.
- Subsequent modifications after obtaining the Design Type with technical evaluation of the modification and its impact on Airworthiness.

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- RULES INTERPRETATION
- GENERAL FRAMEWORK CERTIFICATION.
- INTERIOR CONDITIONING CERTIFICATION
- MODIFICATION IDENTIFICATION

RULES INTERPRETATION

It is common practice to transform civil transport aircraft to military versions. Some civil aircraft, at the end of their operative life in the civil sector, are acquired by the Air Forces and subsequently modified to their specific needs.

In the last few decades, the tendency of the Forties that is to say the Post-war years, has been inverted. Then civilian transport aircraft derived from Military transport aircraft.

Several cases can be cited in this sense:

That of those aircraft borne as a consequence of a military specification and afterwards transformed for civilian use.

Versions which started life as specifically civilian are transformed for military use.

Some manufacturers, develop products whose general specifications are open to both sectors.

It is unusual to find a product that at some moment in its life has not been transformed or had its transformation considered. The long life of the designs made in the Sixties, without precedent in aeronautical history have favoured this situation.

This fact is fundamental in the evolution and interpretation of the Rules.
Spain has not kept aside from this tendency, and various models have been modified, or have been designed to satisfy military and civilian requirements.

In some cases, civil or military versions can be used to carry out identical missions.
The Spanish aircraft CN-235 operate in the military version, e.g. (Morocco) with identical interior conditioning as the versions IB05 Binter Mediterraneo and Binter Canarias or Austral.

Many are the links that allow us to consider both worlds to be mutually permeable. And this has its repercussion on the interpretation of the rules. The evolution of the rules has never been indifferent to this fact.

The Certification Basis must foresee the different uses and missions for one single aircraft with one single Type Certificate. To carry this out, the specific operating conditions of the aircraft are studied and each paragraph is interpreted depending on the mission to be covered by the different configurations, while always being conservative.

GENERAL FRAMEWORK OF CERTIFICATION

The definition of Airworthiness which is applied in Spain is: The ability of an aircraft or weapon to be operated safely within the declared flight envelope and during ground operations from all intended platforms.

According to the Spanish Regulations, all aircraft must fulfil some requirements in order to obtain the corresponding Airworthiness Certificate.

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

The Certifications Basis are established in order to guarantee a specific safety level of the aircraft.
It also ensures that the rules and specifications concerning design, manufacture and maintenance are complied with.
It ensures that the aircraft is operated within the authorised flight envelope and with the corresponding limitations.
The certification is no more than a demonstration that the system complies with the established safety requirements.

In Spain, the Instituto Nacional de Técnica Aeroespacial (INTA) is the organisation responsible for establishing and supervising the Certification processes. INTA is in charge of determining the applicable regulation. In order to draw up the rules, INTA bears in mind the following aspects:

- The mandatory rules.
- The rules proposed by the industry.
- The rules applied in similar products of national use.
- The rules applied by the National Authority of the country of origin of the aircraft.
- That stipulated by the contracting organisation.
- Any other norm the INTA considers necessary once it has consulted the corresponding specialists in a specific system of the aircraft.

In order to determine the Airworthiness Certificate emission requirements, the INTA can count upon the results of the tests of procedures and methods used in the countries of origin.

The specialists, who are members of INTA´s Airworthines Department, of each system will be those, who, referring to the Certification Basis , will make an in-depth study of the safety of the same, and will request from industry an analytical or empirical justification of the norm.

As regards national practice, INTA studies the entire design. It does this through the documents defining the safety of the aircraft and the plans that define it physically. The starting point is an overall and generic vision of the programme. Herein are defined which will be the most important milestones, the safety of the complete system and the implications, in the case of any modification, upon the remaining systems of the aircraft.

Following a Certification plan implies establishing an aircraft reference. This will include:

- Specifications
- Rules and procedures
- Safety Programme Plan
- Design or analysis documents
- Qualification and testing programmes
- Qualification of all the equipment items of the aircraft
- Configuration identification
- Test results
- Manuals

A provisional Type Certificate can be emitted in those cases in which a high degree of knowledge of the aircraft has been reached during the certification process, thus making it possible to establish the airworthiness limitations. Within these limitations the aircraft will be considered flight-safe.

The process starts by analysing the highest level specifications. The manufacturer must demonstrate, analytically and experimentally that:

- The aircraft complies with the applicable regulations.
- The materials and products conform to the Design Type .
- The product components conform to the Design Type plans.
- The manufacturing and assembly processes conform to the Design Type specifications.
- Airworthiness limitations.

As the manufacturer fulfils the milestones, he will thus manifest compliance with the established Certification Basis, with which the Compliance Check List will be generated.

The manufacturer's Configuration Control is that which permits us to know the design. It will be achieved through the physical configuration and functional configuration. Both should completely define the product.

Likewise supervision of the successive stages of evolution of both types of configuration will be carried out. The manufacturer is obliged to carry out a strict Configuration Control that enables the state of the design to be established at each moment of the project.

Finally a Master Drawing List will be drawn up. This will include those assemblies considered to be of major importance, as not all can be included in the Type Certificate of the aircraft. With these items we can determine the design and control its evolution.
The plan is always understood to be the latest consequence of the entire design process.

The Type Certificate is the document by which the Spanish State recognises that the aircraft is safe for flight. It includes: the Design Type, the Data Sheet with the corresponding airworthiness limitations, and any other information considered necessary.

The test reports, calculations and analysis demonstrate that the product complies with the applicable regulation and the specified airworthiness requirements.
All the elements, materials, equipment and accessories used in the manufacture and assembly of the aircraft will

be qualificated and documented, and it will be demonstrated that their integration in the aircraft does not imply any safety infringement for the operation.

INTERIOR CONDITIONING CERTIFICATION

Risks evaluation entails the questions **where, when, how** and **why**, as critical conditions may arise jeopardising the aircraft's safety. What are the critical points of this system during its operation. How, or in what operating conditions might arise abnormal circumstances that affect the correct functioning of the system and what is the sequence or set of circumstances that lead to a system failure.

INTA considers the interior conditioning system as an assembly of those removable items of equipment and furnishings externally mounted on the aircraft or contained in the flight, passenger, cargo and accessory compartments. Includes emergency, buffet and lavatory equipment.

These items can be divided in:

- Flight Compartment
- Passenger compartment
- Buffet/Galley
- Lavatories
- Cargo compartments
- Emergency items
- Accessory compartments

In addition, the following items, although included in different systems, are considered by INTA as a part of interior conditioning certification due to its close relation with safety functional aspects.

- Placards and markings
- Communications
- Electrical Power
- Oxygen
- Water and waste
- Levelling and weighing
- Air Conditioning
- Fire Protection
- Lights
- Doors
- Windows

In order to make a complete assessment of the safety of the system the following aspects are studied:

- Risk analysis, identifying and relating them to the reliabilities.
- Operation and procedures analysis.
- Zonal analysis
- Common failures, cascade failures and their consequences.

Among these critical conditions we can underline:

- Fires caused by failure, electrical faults, malfunctioning or misuse and postcrash fires.
- Accumulation or circulation of toxic gases or smoke in the crew compartment or passenger area.
- Leakage of any inflammable or corrosive fluid.
- Incorrect procedures.
- Mechanical interference of the structure with the launching of cargo, parachutes....
- Cargo displacement affecting the aircraft balance, systems, or crew and passenger area.

Requirements are being solved, thanks to the analysis of the test results as well as the experience of manufacturers, crews, operations, personnel maintenance, safety responsibles, aeronautical authorities and the analysis and investigation of accidents and incidents.
All this has resulted in an improvement of cabins; habitability, noise, operation, maintenance, weight, safety... are some of these aspects.
In this paper only safety aspects will be discussed.

In order to proceed to explain certification requirements, we can divide the requirements demanded of the interior conditioning as a system into five groups:

1.- Use of appropriate materials with a view to improving behaviour in the face of fire and to reduce toxic gases emission during combustion.

2.- Retention of masses in cabins and cargo compartments.

3.- Accessibility of the exits in function of interior space distribution of the cabins.

4.- Systems and aids needed to overcome emergency situation in function of the risks analysis and aircraft reliability.

5.- Weight and balance.

1.- Materials used in order to reduce, combustion, smoke and toxic gases

In the first steps the line in the study of materials for interiors was focused initially on one aspect: Weight.

The behaviour of the materials used in the cabins in relation to fire was considered later, and as a consequence of the problems, incidents and accidents that had occurred. Currently this factor occupies the main place in the selection of the materials.
The regulations which are a live entity, have continually updated, and where in the beginning industrial and/or

textile requirements were applied, specific aeronautical rules have imposed themselves.

Four factors are considered to be especially critical: Fire resistance, Combustion heat, Smoke and Toxic gases emission.
These will be crucial in the choice of materials.

It is possible to improve safety conditions by identifying operational requirements of each aircraft version, cabins or compartments, and in function of the same, to determine the most appropriate materials.

Identifying cabins , we can divide the interior conditioning in two areas with different requirements.

- Crew and passenger areas. Here, materials requirements are: resistance burn.through, heat release, smoke release, flammability, toxic gas emission. These requirements are considered to be the most important safety issues.

- Zones not occupied by persons as cargo compartments, galley, lavatories.
  The most important materials requirements in these areas are: Burn through, heat release, corrosion resistance, structural integrity, smoke release, toxic gas emission.

Nevertheless, design considerations to be taken into account in materials selection are: Cost, Decorative capability, predictability and weight.

The development problems are, to be quite definite, economic.

- The required I+D time depends on the chemical industry

- Tests modelling. Achieve conditions similar to those of the materials behaviour when faced with fire involves certain difficulties. Bearing in mind all the factors such as humidity, ventilation, etc, makes it difficult to obtain valid models.

Both safety objectives and research goals are designed to combat the four critical factors described before.

The emission of gases, heat sources and high temperatures are important hidden health dangers that require extreme care.

Heat emission inside the aircraft forms part of a serious danger for health, and is a factor which affects and modifies structural characteristics of materials used in interior conditioning.

Heat quantity depends on the heating capacity of materials and the amount burnt. When considering cabins as closes systems, with no heating interchange with the exterior, it is in our own best interest to choose low heating capacity materials. This is also a laboratory experiment requirement.

Smoke obscuration is measured in tests too and materials are being compared in this respect.
Air humidity in interior compartments and cabins could reduce heat emission during combustion by 20 %.
The mixture of air blown into the cabin must be about 50% to 75% in order to benefit confort of passengers and crew. Actually this mixture rate is 10% to 20%.
Increasing cabin air humidity could reduce heat emissions.
Water-mist cabin-fire retarding system under examination in order to improve cabin temperatures.

Unfortunately there is no smoke without toxicity. The emissions of CO_2 are produced from the first moment of combustion, and are accompanied by the emission of other products which are even more harmful to health, although these are produced in smaller quantities.

Improved resins combinations or treatments are being tested to reduce toxic emissions such as CO_2, NO, HCN, HCL, H_2S, HBr,..

Work is going on to improve this panorama with research into new materials in order to determine the latest combinations.

But sometimes, improvements in material characteristics regarding a specific requirement can lead to a deterioration in its performance concerning other requirements.
Then a compromise requirements is needed.

In order to instigate a study, we group the materials used in the interior of cabins into four families:

A) <u>Panels</u>

Sandwich panels are the major item in panels construction. They are used for: cabin partitions, sidewall, ceilings...
Bond fly, back skin, facesheet, adhesives, honeycomb and foam are the components of sandwich panel structure.
Material combinations of these components determine the attributes to combat smoke, heat, fire resistance...
Other aditional characteristics demanded of these materials would be: impermeability, cost, decorative capability, predictability and weight.

The requirements for those elements with structural responsibilities cause us to differentiate among:

A-1) <u>Panels without structural responsibilities</u>
For ceiling panels, partitions, dado panels, door and stowage linings, light panels.

Honeycombs panels applications are bulkheads and semi-structural partitions and transparent thermo-stables are used.

A-2) <u>Structural panels</u>
For: Floor panels, galley and consoles structures and panels, overhead lockers, cargo compartments panels.

They are tested for structural responsibility regarding cutting, flexion, warping and buckling and impact.
In some cases they must be resistant to corrosion or chemical attack, especially in galley and lavatory zones.

Their aging is studied to determine the states of environmental humidity, as it is of well worth knowing how the mechanical characteristics degrade as time goes on.

They are usually panels with honeycomb cores covered in glass fibre and phenolic resins. In this sense the panels mounted in passageways and access zones differ from the rest of the panels.

B) <u>Textiles</u>
For: Carpets, upholstery, drapery, belts, harnesses...

Wool is used in seating, curtains, partition coverings and blankets. It is easy to extinguish, and when treated with additives, its characteristics improve. However it has high toxicity, emits hydrocyanic acid and nitrate vapours.
Cotton is less smoke-producing and less toxic, but is more heat sensitive.
Textile plastic materials as: nylon, perlan, rilsan, orlan could be used also, treated with adequate additives.

C) <u>Cushions</u>
Seat cushions specifications includes: flammability, smoke release and toxic gas emission.

D) <u>Thermal and acoustic insulation</u>
For Cabins and cargo compartments insulations.
Characteristics looked for are:
Low heat transfer, high sound attenuation, dimensional stability, corrosion or corrosive vapours emission resistance, moisture resistance, maintainability.

Combinations of materials that considered separately, comply with specifications, may not give the expected results when they are tested together. They are not necessarily as benign as the individual materials. The new combinations must be tested.

2.- Retention of masses in cabin and compartments

The damage suffered by crews and aircraft systems as a consequence of cargo displacements is multiple.
Displacements of cargo can even provoke variation in the aircraft's balance, with the consequent serious implication for flight conditions.
The Airworthiness rules are clear in this respect, and in the last few decades we have seen how this aspect has been paid ever increasing attention.

Once the Certification Basis and the Flight envelope have been established, we find ourselves able to proceed to the study of the loads that each one of the elements must support. It is possible to dimension the structural elements.
In order to determine the strength analysis all elements must be submitted to two sets of critical load conditions:

- Crash landing loads
- Flight load cases

In order to proceed to this study, we can model in the following manner:

- General description of the different elements from a geometrical and structural view point.
- Strength analysis of the structural elements.
- Beam load analysis.

With respect of support items to structure:

- Mechanical properties of materials to be used in design.
- Analysis model
- Strength analysis

Regarding to cargo aircraft or cargo compartments, the size, weight per linear foot and floor contact area weight must be studied to ensure structural integrity.
Structure of the aircraft must permit variation in floor load weights depending upon whether the load is concentred on areas or distributed over the entire floor. The ramp will carry the same weight load.
Retention of masses requirements in ditching must be analysed too.

Respect damage suffered by crews or passengers, harnesses and seats specifications are included, but in this case the requirements are wider than structural retention of masses, and cover the goals of adequates materials and occupants protection.

Passenger and crew shoulder harnesses requirements stablish maximum static and dynamic forces, maximum load between the pelvis and the lumbar column ...in order to protect occupants.

Head injury criteria is applied to seat design and distribution. This criteria affects:
Vertical projection between seats, use of five points shoulder harnesses, flowing curves in seats structural provisions or other nearby structure depends on seats type, aircraft mission and other similar considerations. Head impact must not exceed maximum HIC (Head Injury Criterion) level.

Cushions shall be constructed to have a compression resistance and density providing maximum safety and comfort to the vertbral column.
Additional requirements for ditching must be provided.

3- Exits accessibility as function of the interior space distribution of the cabins

This is the least analytical of all the aspects dealt with. It is based on experience and the tests results obtained. Experimental requirements are defined in rules.

The main problem is to achieve an effective evacuation with passengers that are not necessarily conversant with the use and means of aircraft evacuation.

Improvements are being tried out in this respect, by modelling and carrying out tests. Modelling is complex when it comes to assessing the combination of factors which are present in the evacuation.
As regards improving the evacuation system, the complexity of modelling increases to the point of making it practically impossible, as there are so many factors: the human factor is highly subjective, signal interpretation, attention to safety instructions, motivation of passengers, personal characteristics as age, sex and agility, the effects of toxic products on an individual person , etc.

In this sense, the contents and presentation of safety information is of utmost importance.
Joint flightdeck and cabin-crew answers to cabin problems.
Many tests and experiments have been carried out in this respect, but, faced with the results there is always the doubt whether the model is correct. The costs of modelling increase exponentially in function of their closeness to reality.
Factors influencing evacuation time will be:

- Distance to exit.
- Route taken to exit: over seats or using the aisle. Aisle width
- Existence of safety instructions, training.
- Exit doors configuration. Distance between doors and between doors and seats
- Doors types.
- Seating configuration (troop, sanitary, civil transport...). Vertical projection between the seats. Specially in seats adjacent to the exit.
- Number of bulkhead to pass through in order to exit. Bulkhead width.
- Galley and lavatories and free areas within the exit zones.
- Consoles and racks distribution.
- Remove structural provisions: such as stretcher and parachuting seats...

Working Groups are formed to analyse all these elements using acquired experience.
The objective of the parameter analysis is the final improvement of the aircraft evacuation time.

Conclusions may arise from the study of similar aircraft. In other cases, the conclusion arrives either from computer models to predict evacuation ranges or evacuation tests.

4- Systems and aids required to overcome emergency situations in function of the risks analysis and aircraft reliability

In order to accomplish a safety analysis the aircraft mission, the operation conditions, as well as passenger /crew number and aircraft furnishing, must be defined.
Then, it will be possible to determine those items required to overcome the emergency situations.

INTA, considers as Emergency items those ones carried for use in emergency procedures. They include items such as evacuation equipment, life rafts, jackets, emergency locator transmitters, underwater locator devices, first aid kit, incubators, oxygen tents, medical stretchers, landing and signal flares, drag parachutes, evacuation signalling system etc...

The intention to continue reducing the cabin's vulnerability to fire and the secondary effects of combustion, obliges us to take some lines of approach considering as emergency items those ones that, although belongs to other systems, are included on the following functionalities:

a) Reduce the evacuation time
b) Improve the cabin survivability conditions in emergency situations during flight time or during the time needed to evacuate

Systems involved in INTA philosophy are:

- Fire Protection
- Oxygen
- Air Conditioning
- Markings and placards
- Communications
- Lights
- Doors

4.1 Fire Protection.

Relevant works in this area are:

a)- Improvement of the early fire detection tools in cabins, toilets and compartments.

Accident analysis shows that a high percentage of fires on-board aircraft can be avoided with a suitable knowledge of the ignition sources and circumstances.

Adequate treatment of these fire sources with methods of detection and extinction appropriate for the sources and circumstances of each case could help these situations, either by remedying them or by delaying the effects of the fire on the cabin and its occupants.

Specifying carefully the requirements of the Fire Detectors as response thresholds, and relating them to the zones or functions of each one. Determining the optimum placement of each one exclusively in function of safety.
Analysing and classifying those zones that experience identifies as critical ones, and where hidden combustion could occur, for example, cargo compartments, lavatories , the spaces between the ceiling panels and the fuselage covering, , air conditioning system...

b)- Installation of an adequate Warning System in cockpit
Training cabin crew in order to improve their basic aircraft technical information.

c)- Improvement of the response of the extinction systems and adapting them to the real needs of each individual zone and circumstance.
Identifying the critical moments in which these situation could arise (in flight, ramp fire, post-crash fire), in order to determine the specific situation and take the necessary measures or procedures.

Identifying Fire Classes, the predominant materials in the zone, and in function of all this to determine the optimum fire extinction system and extinguishing agent.

Combustion could be beaten: decreasing oxygen, flammable materials or temperature below the inflammation limit.

Knowledge of different kinds of fires inside the aircraft could help to a faster extinction.
Water extinguisher for ordinary flammable materials as paper, wood and textile.
Foam can extinguisher of foam for oils, flammable liquids etc..., that floating to the surface do not allow combination between oxygen and flammable materials.
Inert gas extinguishers replace to the spray liquid ones for toxic emission products.

4.2- Oxygen

Oxygen mask and oxygen bottles requirements, number, distribution and accessibility in the cabin, in terms of: mission, flight parameters and passenger or tripulation number.

4.3 Air conditioning

Developing crew aids in order to improve visibility under smoke conditions in cockpit.

The existance of smoke in the cockpit has provoked multiple incidents which have posed serious problems for the controlability of the aircraft.

Opening the windows does not solve the problem. It is very difficult to eliminate the smoke entirely, and the resultant noise only worsens operating conditions.

Two ways of solving the problem are:
Improvment of the ECS in the cockpit in order to renovate the air rapidly and to the supress the smoke independently of the windows configuration.
Development of sight systems, masks and inflatable hoses that occcupy the space existing between the instrumnets and the windows and the pilot's mask.

4.4 Markings , signals and colours into cabins.

Passengers are not conversant with aircraft evacuation means.
Training and technical information about aircraft must ensure a minimun knowledge of aircraft general arrangements and evacuation aids with a view to improvimg evacuation conditions for passengers.

Doors and exits markings are required to have increased readability, letters and numbers must be dimensioned according to specific requirements.
Doors and emergency exits identification and operating control are the most critical items in this respect. Operation of aircraft external doors must be be clearly marked. Likewise the contour of the area to be broken in or cut- out must be clearly identified.
Liferaft release and flotation controls will be identified also, and operating instructions must be indicated.
Markings, lettering and signals such as emergency and warning decals, must have an adequate contrast to the different backgrounds and environmental illumination.

Markings must identify structural provisions as: litter installation guide, roles, cables, straps and cargo winch, fittings, body stations maximum cargo capacity for both cargo tie-down and litter/troop seats versions .
Standardizationof the signs is extremely important, as the use of an adequate standard renders subsequent modifications unecessary,and with time, gives rise to words of an iconographic nature such as EXIT.
Literature and iconographic markings must be normalized.
This act considerably improves on-board communication.

Common comunication requirements between military and civilian aircraft for emergency procedures, with similar operation could improve response in emergency situations and correct procedures used in abnormal situations.

Highly subjectve interpretation and motivation advise Testing, after design, and the use of evacuation and emergency procedures.

The best way to improve the efficiency of on-board communications, be they instructions using oral or writen lenguage, or symbols, is to incorporate improvements arising from the results observed in the tests.

Regarding interior colours, specifications could be in accordance with the stipulations of the applicable aircraft contract, or with aplicable directives in consonance with service requirements.

Colour schemes and combinations will be selected according to: the characteristics of the various aircrew stations, physiological and psychological well-being of the aircrew, compartment size and lighting, operational aera of the aircraft and spacious workspaces.
Standardized colours used in interiors are in function of items to be painted.

4.5 Communications, lights and batteries.

Providing a post crash electrical self energizing system in order to ensure operation under general failure conditions:

A general electric power failure of the aircraft must not compromise the aircrafts evacuation aid systems.
The complete system shall consist of a housing containing batteries, switch, and transmitting elements.
Batteries will not be connected to the external power source.

The power supply to the following systems must be assured:
Floor Proximity Escape Path Marking
Exits areas illumination.
Acoustic signals near exits.
Emergency marking and signals ilumination.
Communication system

Light sources shall provide floodlight or uniform candle distribution and shall continue to operate during a period of time even when immersed in salt water.
Light sources must have a protective coating so that extreme or emergency conditions should be avoided.

5.- Weight and Balance

The weight and centering requirements will also be determining factors in the aircraft interior configuration.
Concerning weight, material selection is very simple. Once these comply with all the atructural requirements and behaviour under fire conditions, etc., the lightest materials will be selected, bearing in mind the production and maintenance costs. These will always be directed towards a reduction in cost.

Reagrding Balance, once the mission has been established, all the possible load conditions must be taken into account. We will divide the cabin/s in order to instigate the study of the possible loads:

- Cockpit
- Passenger or troop area
- Crew rest zone
- Service zone: galleys, toilets, cupboards, consoles, observation posts.
- Cargo compartments
- Exit zones

Once the aircraft has been divided into zones, we will proceed to study all the possible loading cases and the different combinations of the same. The objective being to keep within all teh flight plans in conditions of optimum centering, or to keep to them as closely as possible.

We will focus our attention on the safety requirements mentioned previously, always refering to the following interior conditioning versions:

- Cargo transport
- Troop transport, parachute troops
- Civil transport
- VIP transport
- First aid transport
- Maritime patrol
- Electronic War
- Calibration
- Photographic reconnaissance versions
- Fire extinction
- etc.

The interior conditioning requirements adjust the interior configurationin design finally as being a balance of multiple requirements that often prove to be incompatible.

MODIFICATIONS IDENTIFICATION

Modifications are considered to be those changes that require a new aircraft design, or a partial or complete redesign of the components, installation of equipment or systems.

The aircraft covered by a specific Type Certificate can be modified.
Oncce the Certification Basis are established, and the product obtained as a result of the requirements of the same, and the compliance of the design with respect to the specifications verifed, the aircraft will obtain its Type Certificate. From this moment ont the design is frozen, and evolution control will be applied in order to classify and assess any modifications introduced.

Two circumstances are given that iniciate the modfication process durign the design's life:

1.- Introduction of modifications during chain production.

2.- During aircraft operation. Once the aircraft has been delivered, and if it is necessary for reason of operations requirements, safety or exploitation costs.

The first step in the modification analysis is to classify them.
The modifications are greater or smaller considering airworthiness impact.

The modifications made can be as a consequence of:

- Customers requests
- Improvements introduced into the serie.
- Design errors
- Airworthiness request
- Documentation errors.

In already certified aircraft to which modifications will be introduced, the following data must be specified:

- Configuration of the aircraft prior to the introduction of the modifications.
- Type Certificate that covers the previous configuration.It includes the original Data Sheet with the Airworthiness Limitations and the Certification Basis.
- List of Service Bulletins or Technical orders that have been introduced during the lifetime of the aircraft.

Among the major modifications there are some that could provoke the obtention of a new Type Certificate according our regulations. These would be:

- Change in the number of engines or in the propulsion principle. In the case of turboprop aircraft the changes in the number of blades, type or change of pitch.
- Operation changes
- When a set of modifications such as general configuration, power, weight, speed... imply a substantial change in the Type Design of the aircraft.

The major modifications that affect the revision of the Type Certificate must be included in the data sheet.

With regard to the interior conditioning, major modifications would those that affect the door accessability, modification on interior elements, evacuation conditions or aids, and changes in materials, weight and centering or structural stipulations for the transport of products dangerous for the flight.

A large percentage of modifications refer to interferences in the assembly: Skirting, blankets, panels, cable packages etc. A multitude of minor discrepancies referring to design documentation, in some cases also to documentation errors or extensions and changes in the system items effectiveness.

Once the design has been frozen and it has been demonstrated experimentally that it complies with the specifications and the Certification Basis, the chain manufacturing commences. Each series number differs from the rest in the improvements incorporated to the series by lots, in the specific modifications of the version for a particular customer, and in the manufacturing deviations and waivers.

A **Conformance Certificate** is issued for each one of the aircarfts serial number. This is the document by which the stipulations of the rules covers any equipment item of the aircraft manufactured according to the technical specifications defined in the Design Type.
The following documentation is essential in order to issue this certificate:

- Design type standard
- Configuration identification
- List of deviations and waivers
- List of functional conformity tests
- Acceptance of flight tests
- Data sheet.

Continuous Airworthiness

The operator must be notified of all the modifications that affect the Design Type, in order to correct an uncertain condition of the product.
The manufacturer will inform the operators of the affected product of all the approved modifications.

Service Bulletins

Modifications are introduced to aircraft that are in service and in the hands of the operator.
These improvements may or may not affect the safety of the aircraft.
If they do not affect the aircraft's safety, they are introduced in a voluntary manner by the operator.

As with all the other modifications, the content is studied in the same way, and the effectiveness is likewise checked. A single modification is implanted in the majority of cases to aircraft pertaining to different operators, that is to say, to different versions.

CONCLUSIONS

a) Three of the five groups of requirements are a direct consequence of fire in cabins:

- Use of appropriate interior materials
- Interior space distribution of the cabins.
- Emergency items.

Fires caused by system failure, malfunctioning or misuse , postcrash fires and their consequences obligue us , in interior design, to consider fire as the most critical aspect.

b) Conflict among different requirements normally occurs, for example between: fire resistance versus smoke emissions or evacuation requirements and emergency items versus mission needs.

c) Conflicts when civil requirements are use into the military scenarios. Generally, civil sector is more conservative than military.

d) The Certification of Interior Conditioning involves multiple tasks and disciplines. There is a dependency of other aircraft system and even other non aeronautical industry as the chemical.

REFERENCES

- Manufacture´s Technical Data. ATA.
- Airborne Equipments AECMA
- Code of Federal Regulations.FAA
- Joint Airworthiness Requirements.JAA

PROGRES DANS LES ESSAIS DE TENUE AU FEU DES COMPOSANTS DE REACTEUR ET NACELLE

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1. RESUME

La démonstration de tenue au feu des composants de réacteur, de nacelle (et d'avion) nécessite souvent d'effectuer des essais en présence d'une flamme générée par un brûleur. Vers les années 50, principalement pour vérifier la tenue au feu des tuyauteries de carburant/huile et le fonctionnement des détecteurs d'incendie, des documents normatifs ont été établis et des moyens d'essai associés (brûleurs) ont été mis au point.

Plus récemment, l'utilisation de plus en plus courante de ces moyens pour démontrer la tenue au feu d'éléments et d'équipements très divers installés sur moteurs/ nacelles d'avions modernes a mis en évidence certaines lacunes concernant les normes ainsi que les brûleurs existants.

Le but de la publication est de montrer le travail effectué par SNECMA , en association avec les Services Officiels français (STPA) et le Centre d'Essais de Propulseurs (CEPr) pour améliorer les matériels existants, simplifier leur utilisation et surtout les rendre équivalents , notamment les brûleurs à fioul et propane. L'étude présente aussi les moyens d'analyse développés et utilisés à Snecma, en corrélation avec les essais.

2. INTRODUCTION

En matière de transport aérien, les précautions à prendre contre le feu sont réglementaires.

Pour l'avion, elles dépendent des textes de la JAR25 para. 851 à 867 et 1181 à 1207 pour ce qui concerne la certification européenne, FAR25 para. 851 à 869 et 1181 à 1207 en territoire des Etats-Unis d'Amérique.

Pour les moteurs à réaction , ce sont les textes de la JAR-E 530 et 570 qui traitent de ces sujets pour la certification en Europe et FAR-33-17.et 71 aux USA.

En plus des précautions prises par le concepteur et dictées par les règles de l'art, les pièces, les composants , les accessoires des réacteurs et de leurs nacelles situés dans les zones désignées "zone feu" , voire dans les zones adjacentes, doivent posséder, selon ces règlements, des qualités de résistance au feu qu'il faut démontrer aux autorités pour obtenir le Certificat de navigabilité.

Souvent, faute de références, d'expériences ou de moyens d'analyse, la démonstration de tenue au feu doit être établie par des essais en vraie grandeur, en présence d'une flamme.

3. PROBLEME RENCONTRE

Les procédures d'essais peuvent être mentionnées dans les règlements (ACJ pour l'Europe , AC pour USA) ou, à défaut, dans des documents explicatifs acceptables par l'Autorité ; souvent ce sont des normes.

En plus des procédures, ces documents décrivent les matériels à utiliser pour générer la flamme et les appareils associés; il s'agit de brûleurs fonctionnant avec des carburants soit liquide (fioul) , soit gazeux (propane) et de matériels de mesure thermique (thermocouples, débitmètres, calorimètres, etc...).

A titre indicatif, nous donnons dans le <u>tableau n°1</u> un échantillonnage (non exclusif) de quelques produits et caractéristiques des matériels d'essai au feu, selon les normes les plus courantes.

Dans les années 80, pour les besoins de conception d'accessoires et d'éléments de structures d'inverseur du moteur CFM56-2 destiné au B707 , puis au DC8, SNECMA a entrepris une campagne d'essais de développement de tenue au feu dans un banc agencé autour du brûleur à propane décrit par la norme américaine AS401B (ref 1). Nous avons très rapidement découvert que ce brûleur délivrait une flamme thermiquement moins puissante que celle du brûleur à fioul mentionné dans d'autres normes (tableau 1).

En effet, ce brûleur à propane, initialement utilisé dans les années 50 (1ère version de l'AS401B en 1947) était prescrit principalement pour la vérification (essai qualitatif) des détecteurs d'incendie. En aucun cas, il n'était réellement adapté , avec les réglages proposés, à restituer une flamme équivalente à celle générée par un feu de carburant d'avion ; ce que simule bien par contre, le brûleur à fioul.

* d'un point de vue thermique : une flamme se caractérise essentiellement par les deux paramètres suivants :

  φ : la densité de puissance dite "flux thermique" en kW/m^2 ($Btu/ft^2/sec$) proportionnelle au débit carburant consommé;

  T : la température en °C/°K (°F/°R) proportionnelle à la richesse (débit carburant/ débit comburant).

Ce sont ces deux paramètres qui, compte tenu des caractéristiques géométriques (surface, masse) et physico-thermiques (conductivité, chaleur massique, émissivité) , propres à un accessoire, régiront sa température d'équilibre en fonction de son temps d'exposition dans la flamme.

Pour la plupart des feux en espace ouvert, notamment feux d'huile, de carburant , il a été vérifié que dans les flammes :

φ est de l'ordre de 120 kW/m^2 (10 $Btu/ft^2/sec$)
pour T = 1100°C (2010°F)

Ces valeurs sont celles que l'on trouve notamment dans les documents AIR 1377A-AS1055B-FAA PPER 3A. (ref 3-2-4).

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

Dans un premier temps, pour restituer la sévérité thermique de ces deux paramètres avec le brûleur à propane, nous prolongions systématiquement la durée d'essai initialement requise sur la base d'une analyse thermique ; un exemple de cette façon de procéder est donné sur la figure 1.
Bien que satisfaisante, cette méthode nécessitait des calculs longs à mettre en oeuvre à cause de la géométrie complexe des accessoires et qui, de toute façon , devaient obligatoirement être réitérés à chaque cas d'espèce.

Il a donc été décidé, plutôt que d'augmenter la durée d'essai dans la flamme, de rechercher des nouveaux réglages du brûleur à propane qui permettent de restituer rigoureusement le flux thermique et la température du brûleur à fioul.

Nous avons effectué ce travail en association avec le Centre d'Essais de Propulseurs (CEPr) de Saclay, en région parisienne et les Services Officiels français (STPA). Ces travaux ont, par la suite, permis d'élaborer les conditions d'utilisation du brûleur à gaz donné en exemple dans les normes actuelles : ISO 2685 Internationale (ref.5) et AIR 978B Française (ref 6).

4. CARACTERISATION DU BRULEUR A PROPANE AS401B

Le brûleur est décrit en détail dans les normes ref 1,5 et 6.
Il est constitué d'un bol de 180mm de diamètre. La flamme qu'il délivre est issue de la combustion d'un mélange de propane et d'air primaire, un débit d'air secondaire permet, tout en participant aussi à la combustion, d'affiner le réglage de la température de la flamme et de refroidir la grille accroche-flamme. Ce brûleur est illustré sur la figure 2. Les débits sont régis par des chambres à orifices calibrés dont les pressions, de part et d'autre, sont mesurées et réglées selon la norme ref.1 aux valeurs suivantes :

ΔP gaz = 25mm H_2O (0,99 in H_2O)
ΔP air primaire = 235mm H_2O (9.25 in H_2O)
ΔP air secondaire = 279mm H_2O (11.0 in H_2O) légère variation possible pour régler la température.

4.1. Mesure de la température de flamme

Le brûleur fonctionnant avec ces réglages , nous avons mesuré la température de la flamme sur toute sa surface à différentes hauteurs et selon un pas carré de 25mm x 25mm (1 pouce x 1 pouce), tout comme pour le brûleur à fioul (figure3). Ces mesures ont été réalisées à l'aide d'un peigne de six thermocouples chromel-alumel espacés de 25mm (1 pouce) - figure 2. La moyenne des points de mesure situés au centre de la flamme sur environ 25 % de la surface est tracée sur la figure 4 en fonction de la distance du peignage.

Les résultats montrent qu'avec les réglages d'origine , la température au centre du brûleur à propane est presque toujours inférieure à celle du brûleur à fioul prescrite à une distance de 100mm (4 pouces). Pour restituer ce niveau de température (2000°F ± 150/ 1093°C ± 83), il est nécessaire de diminuer le débit d'air secondaire : ΔP = 100mm H_2O (4 inches H_2O) au lieu de 279 mm H_2O (11 in. H_2O).

4.2. Mesure de l'intensité - flux thermique

Dans cette première phase d'essais , on a montré que l'on pouvait obtenir avec ce brûleur à propane une température de flamme entre 50 et 100mm de distance (2 à 4 pouces) équivalente à celle du brûleur à fioul à 100mm (4 pouces), ceci avec les réglages suivants :

ΔP gaz = 25mm H_2O (0,99 in H_2O)
ΔP air primaire = 235mm H_2O (9.25 in H_2O)
ΔP air secondaire = 100mm H_2O (4 in H_2O)

Dans un second temps, nous avons mesuré le flux thermique en utilisant la même procédure que pour le brûleur à fioul notamment le même calorimètre tubulaire décrit dans les documents ref 3 et 4. (fig 2).

La figure 5 illustre le flux thermique mesuré en fonction de la distance du brûleur et l'on s'aperçoit ainsi que l'intensité de la flamme est inférieure de 16 % à 27 % , selon la distance, à celle mesurée en moyenne avec différents brûleurs à fioul (ref 4) à 100mm.

5. EQUIVALENCE AU BRULEUR A FIOUL

Selon les indications du paragraphe 3, on voit que pour augmenter le flux de chaleur , tout en conservant la même température, il faut augmenter le débit de carburant de la même proportion que le débit comburant pour conserver la même richesse de combustion. C'est ce que nous avons réalisé dans une troisième phase en augmentant les débits de gaz et d'air primaire à deux reprises pour aboutir aux résultats de la figure 6 qui montrent que le flux thermique, entre 50 et 75mm (2 et 3 pouces) de distance, est toujours supérieur aux mesures moyennes (ref 4) du brûleur à fioul (116 kW/m^2 - 10.2 $Btu/ft^2/sec$) lorsque les réglages sont les suivants :

ΔP gaz = 45mm H_2O (1,77 in H_2O)
ΔP air primaire = 435mm H_2O (17,13 in H_2O)
ΔP air secondaire = 300mm H_2O (11.81 in H_2O)

Dans ces conditions, nous avons vérifié que la température au centre de la flamme reste toujours largement comprise dans les tolérances souhaitées et trés comparable aux mesures effectuées par le CEPr avec le brûleur à fioul (fig. 7).

Remarque : nous avons tenu aussi à vérifier que ces essais étaient bien répétitifs. Aussi, pour ces mêmes réglages et à une distance de 75mm (3 pouces), la température au centre de la flamme mesurée sur un autre exemplaire de brûleur à propane était très voisine : 1109°C pour 1114°C (2028°F pour 2037°F) avec un flux thermique de 112,7 kW/m^2 pour 116,9 (9,92 $Btu/ft^2/sec$ pour 10,29).

6. VERIFICATION DE L'EQUIVALENCE

L'équivalence des deux types de brûleurs étant établie, sur la base de la température et du flux mesuré en régime stabilisé, il était important de vérifier cette équivalence sur un véritable équipement en démontrant que les deux types de brûleur produisent la même évolution transitoire de température de l'équipement pendant la même durée d'essai.

Pour ce faire, nous avons utilisé un module de filtration de circuit d'huile du moteur CFM56-3/B737. Deux exemplaires rigoureusement identiques de cet accessoire ont donc été soumis à un essai "d'épreuve" au feu de 15 minutes :
-l'un avec le brûleur à propane dans les installations SNECMA à Villaroche,
-l'autre avec le brûleur à fioul LENNOX au CEPr à Saclay.

Chacun des modules était équipé de quatre thermocouples, trois situés face à la flamme, un à l'opposé (fig 8).
L'installation d'essais est schématisée sur la figure 9.

Les conditions de circulation de l'huile étaient fixées à :
- débit = 350 l/h ± 10 (92,5 US Gal/hr)
- température d'entrée en début d'essai : 65°C ± 5 (149°F)
- volume d'huile = 50 l (13,2 US Gal)

Ces conditions correspondent à celles du circuit d'un moteur en vol lorsqu'il a été coupé par le pilote lors d'une alarme incendie et qu'il continue à tourner en autorotation.

Les évolutions des températures en fonction du temps sont présentées dans la figure. 10 pour les deux essais ; on constate que :

- les temps de stabilisation sont assez courts et très voisins pour les deux tests (environ cinq minutes)

- du côté de la flamme, les évolutions de température (T/C1-T/C2-T/C3), et les valeurs maximales atteintes en fin d'essai sont très proches dans les deux cas; à l'opposé (T/C4) , les températures sont pratiquement identiques

- après 15 min, l'échauffement de l'huile était pratiquement le même:
  ΔTH = 25°C (45°F) avec le brûleur à fioul
  ΔTH = 21°C (38°F) avec le brûleur à gaz

- il est aussi remarquable de noter qu'après cinq minutes d'essai (qui correspondraient à un essai de "résistance" au feu) toutes les températures sont très proches.

Les contrôles effectués après les essais sur les deux articles n'ont révélé ni fuite d'huile, ni endommagement. Au cours de cette campagne, d'autres essais de comparaison des brûleurs ont permis de confirmer leur équivalence sur des structures minces et légères : tôle , panneau nid d'abeille d'alliage léger.

7. CONCLUSIONS - REMARQUES

Les essais d'évaluation thermique du brûleur à propane ont montré, dans un premier temps :

- qu'avec les réglages proposés par la norme AS401B, ce brûleur -entre 50 et 75mm de distance (3 à 4 pouces)- délivre une flamme moins sévère en température et en flux de chaleur que celle des brûleurs à fioul (ref 2 et 4) à une distance de 100mm (4 pouces)

- que pour obtenir une flamme vraiment équivalente, il faut augmenter notablement les débits :

ΔP gaz = 25mm $H_2O \rightarrow$ 45 (0,99 in $H_2O \rightarrow$ 1.77)
ΔP air primaire = 235mm $H_2O \rightarrow$ 435 (9.25 in $H_2O \rightarrow$ 17.13)
ΔP air secondaire= 100mm $H_2O \rightarrow$ 300 (4 in $H_2O \rightarrow$ 11.81)

En second lieu et dans ces conditions, l'équivalence thermique est vérifiée par un essai d'épreuve au feu sur un équipement en grandeur réelle.

Les résultats de ces travaux ont contribué à établir la méthode d'essai de tenue au feu des équipements d'aéronefs avec utilisation du brûleur à gaz. C'est à partir de cette méthode et des procédures décrites dans les documents américains (ref 2-3-4) concernant les brûleurs à fioul qu'a été élaborée la version actuelle de la Norme Internationale ISO 2685 (ref 5) : "Aéronefs : méthode d'essai en environnement des équipements embarqués. Résistance au feu dans les zones désignées "zones de feu"" , à laquelle se réfère le règlement européen (JAR 25- ACJ25-1181).

C'est avec cette procédure que SNECMA utilise dans ses installations le brûleur à propane pour homologuer, certifier ses propres matériels ou ceux d'autres constructeurs. Ainsi, durant ces quinze dernières années, plus de 300 essais de développement ont été réalisés , de même que 50 essais de certification comme, par exemple , les accessoires moteur tels que :
- pompes à huile - boîtes d'engrenages (M88-CFE738-TRENT)
- vannes d'air, de carburant : (CFM56 tous types - M88)
- réservoirs d'huile (CFM56 tous types - GE90)
- tuyaux flexibles (CFM56 tous types - M88 - GE90)

et les éléments de structures nacelle/ inverseur comme :
- capots en nid d'abeille, joints nacelle, cloisons feu (CFM56 tous types).

En plus de ces progrès acquis au niveau des moyens d'essai , des améliorations récentes ont été réalisées dans le domaine des analyses thermiques pour la conception des accessoires en vue de leur tenue au feu. C'est ainsi que le code de calcul SNECMA THBN1200 qui permet de modéliser la flamme et l'accessoire dans les trois dimensions et d'obtenir les températures en tout point en fonction du temps a été abondamment corrélé par des essais de développement de tenue au feu. Son utilisation permet de prédire avec une bonne confiance les niveaux de température que l'on obtiendrait lors d'un essai de démonstration au feu et ainsi de trouver rapidement les solutions technologiques les plus appropriées.

Nota : THBN signifie Thermique par Bilan aux Noeuds.
La pièce à calculer est partagée fictivement en une multitude d'éléments géométriquement simples (jusqu'à 9999 dans la version THBN1200) et suffisamment petits. Le code effectue le bilan thermique au centre de gravité de chaque élément et en déduit la température en régime transitoire.

Il n'est pas rare d'avoir recours à ce code pour démontrer aux Autorités la tenue au feu d'un article par similitude et/ ou transposition des résultats d'un essai au feu d'un article semblable ou bien pour chiffrer l'influence d'un paramètre qu'il n'est pas toujours possible de restituer lors d'un essai.

Deux exemples de corrélation calculs/essais sont donnés figures. 11. et 12.

L'incendie à bord d'un aéronef est quelque chose de terrible. Le devoir des concepteurs que nous sommes est de prendre en compte cet aspect dès le début des études de nos matériels, en imaginant des technologies et des systèmes qui, d'une part rendent extrêmement peu probable la génération d'un feu et, d'autre part, garantissent malgré tout, dans ce cas peu probable, une tenue au feu irréprochable des articles concernés et qui va au-delà des règlements.

L'amélioration sans cesse des moyens d'essais et de calcul contribuera à cet objectif et il est encourageant de constater que les efforts consentis ces dernières années par les Industriels, en coopération avec les Autorités, pour en particulier améliorer les moyens d'essais de résistance au feu, ne sont pas étrangers aux bons résultats enregistrés vis-à-vis des cas de feu rencontrés en service commercial ; pour ce qui concerne SNECMA et ses partenaires motoristes :
de 1979 à 1996 : 1 seul feu nacelle contenu pour plus de 80 millions d'heures de vol de la flotte CFM56.

8. REFERENCES

1. Norme SAE AS401B revised 15.01.61
   Powerplant fire detection instruments. Thermal and flame contact types (reciprocating engine powered aircraft)
2. Norme SAE AS1055B revised 01.03.78
   Fire testing of flexible hose, tube assemblies, coils, fittings and simular system components
3. Norme SAE AIR1377A revised 01.80
   Fire test equipment for flexible hose and tube assemblies.
4. FAA PPER n°3A revised 03.78
   Standard fire test apparatus and procedure (for flexible hose assemblies)
5. Norme ISO2685 - first édition 1992-07-15
   Aircraft environmental conditions and test procedures for airborne equipment - Resistance to fire in designated fire zones.
6. Norme Française AIR978B édition 3 30.10.87
   Essais de tenue au feu des matériels aéronautiques. Définitions de la flamme standard et procédures d'emploi des brûleurs.

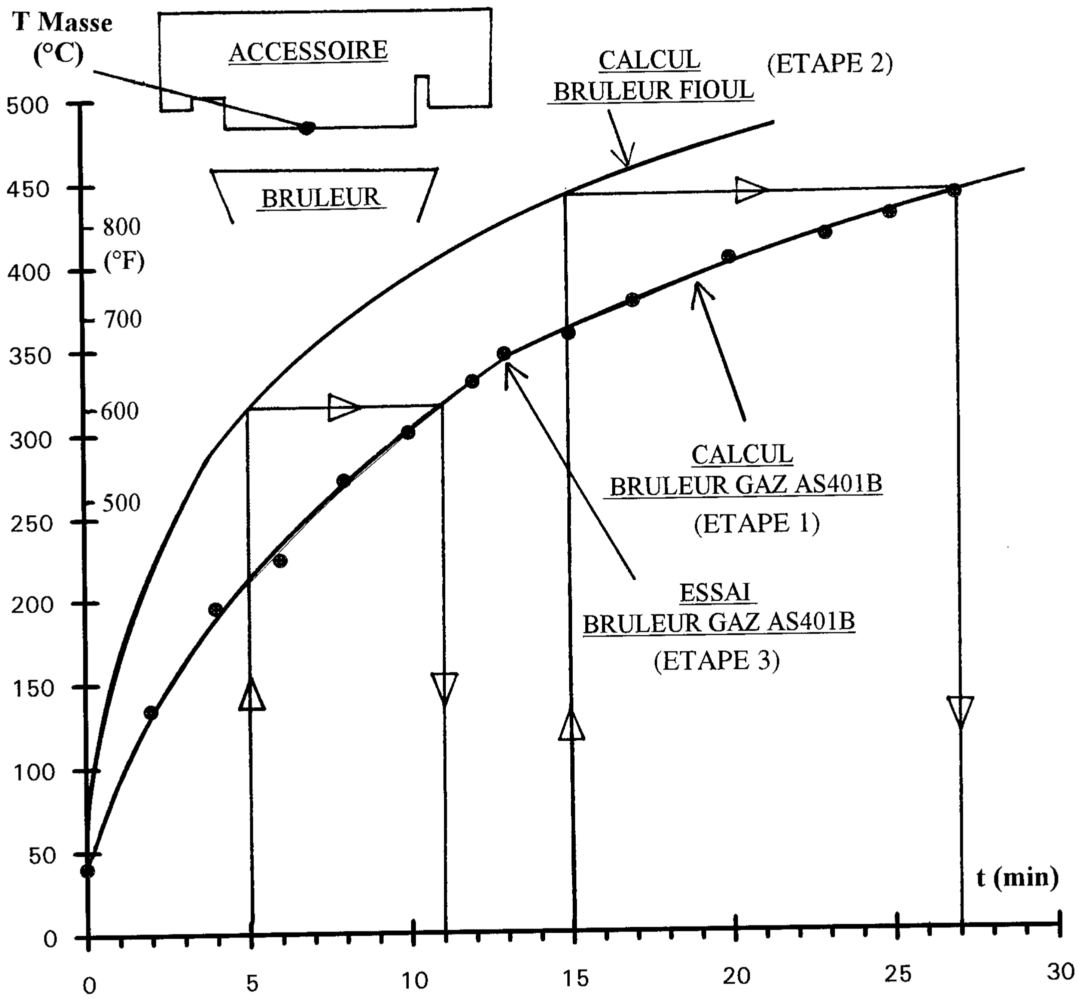
CARACTERISTIQUES DE MATERIELS D'ESSAI AU FEU

	NORME				
EXIGENCE	**AS 401B**	**AIR 1377A AIR 1055B FAA PPER3A**	**AC 20-135**	**AS 4273**	**ISO 2685**
TEMPERATURE DE LA FLAMME	2000 F (1093 C)	2000 ± 150 F (1093 ± 83 C)	2000 ± 150 F (1093 ± 83 C)	1850 à 2150 F 1010 à 1177 C	1100 ± 80 C (2012 ± 144 F)
DENSITE DE FLUX THERMIQUE	Non spécifié	10 ± 1 Btu/ft²/s 113.5 ± 11 kW/m²	Au moins 9.3 Btu/ft²/s (au moins 105.6 kW/m²)	Au moins 9.3 Btu/ft²/s (au moins 105.6 kW/m²)	116 ± 10 kW/m² (10.2 ± 0.9 Btu/ft²/s)
TYPE DE BRULEUR	Gaz	Fioul	Fioul,gaz ou autre bruleur agréé par la FAA	Fioul	Fioul,gaz ou autre bruleur respectant la flamme normalisée
DISTANCE ENTRE BRULEUR ET ECHANTILLON	3 in (75 mm)	4 in (100 mm)	Egale a la distance utilisée pour la mesure de la température de la flamme et du flux thermique	4 ± 0.5 in (100 ± 12 mm)	Egale a la distance donnant les conditions de flamme normalisée 4 in (100 mm) pour le bruleur a fioul et 3 in (75 mm) pour le bruleur à gaz

TABLEAU - 1 -

EQUIVALENCE BRULEUR A GAZ AS401B /BRULEUR A FIOUL EN TERME DE DUREE D'ESSAI

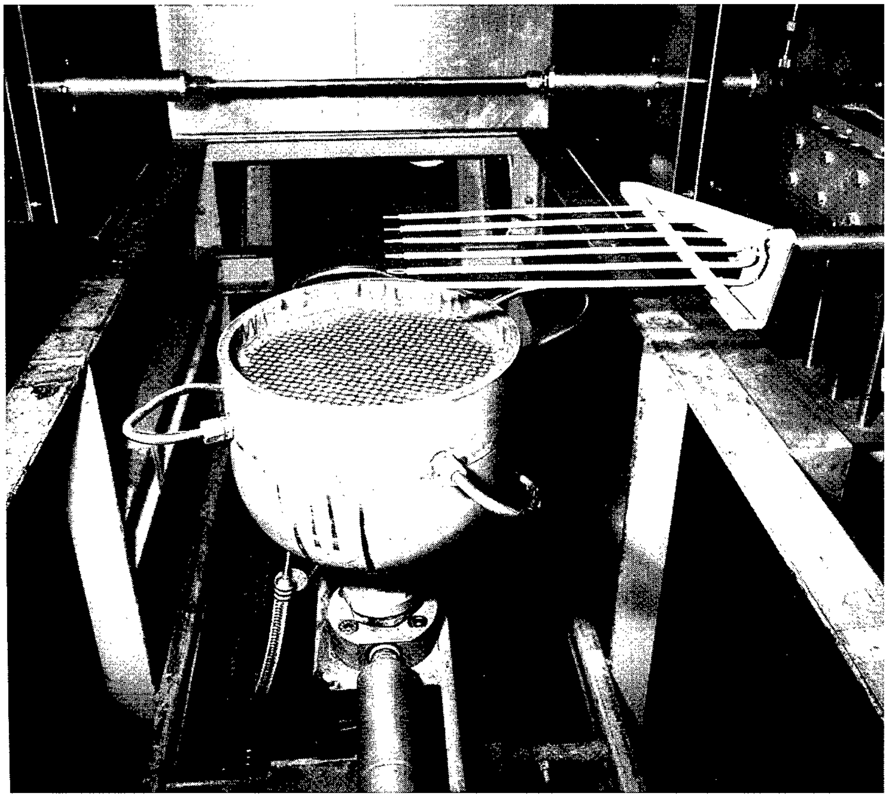
BRULEUR A GAZ AS 401B	CARACTERISTIQUE DE LA FLAMME	BRULEUR A FIOUL AS1055B FAA PPER3A
91 kW/m² à 1100 C (8 Btu/ft²/s à 2000 F)	FLUX THERMIQUE MESURE	115 kW/m² à 1100 C (10.1 Btu/ft²/s à 2000 F)



BRULEUR A GAZ AS 401B	EQUIVALENCE DES DUREES D'ESSAI	BRULEUR A FIOUL AS1055B FAA PPER3A
10'55"	RESISTANCE AU FEU	5'
27'	EPREUVE DU FEU	15'

FIGURE 1

156620



BRULEUR A PROPANE AS 401B

FIGURE 2

180	370	630	658	532	218	49
582	710	900	1000	688	280	108
621	940	1025	980	870	485	223
659	890	1020	1020	1000	695	401
342	720	1015	833	715	620	319
280	571	725	635	414	285	139

BRULEUR A PROPANE AS401B

777	954	938	1008	993	1014	1031	1046	994	936	770
970	953	1033	1082	1087	1088	1090	1090	1064	992	937
976	1008	1062	1092	1086	1081	1064	1079	1084	1046	909
637	917	1028	1006	968	954	932	928	1028	1028	761
393	718	869	759	670	675	573	641	843	821	382
356	342	339	313	296	298	332	343	388	289	216

BRULEUR A FIOUL (LENNOX OB-32)

PAS DU PEIGNAGE 25x25 mm (1x1 in)

EXEMPLE DE RELEVE DE TEMPERATURES (C)

FIGURE 3

TEMPERATURES DU BRULEUR A PROPANE AS401B

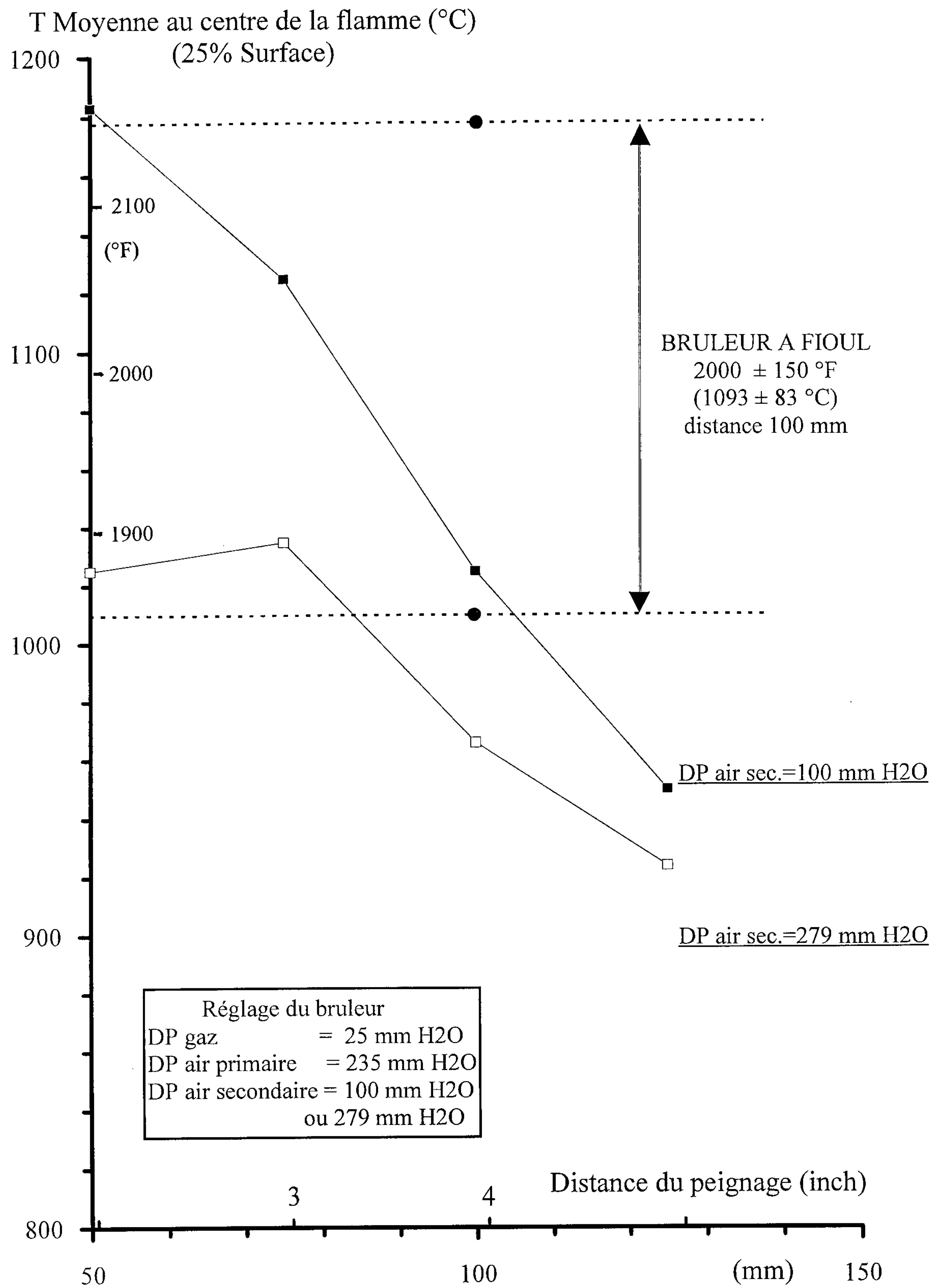
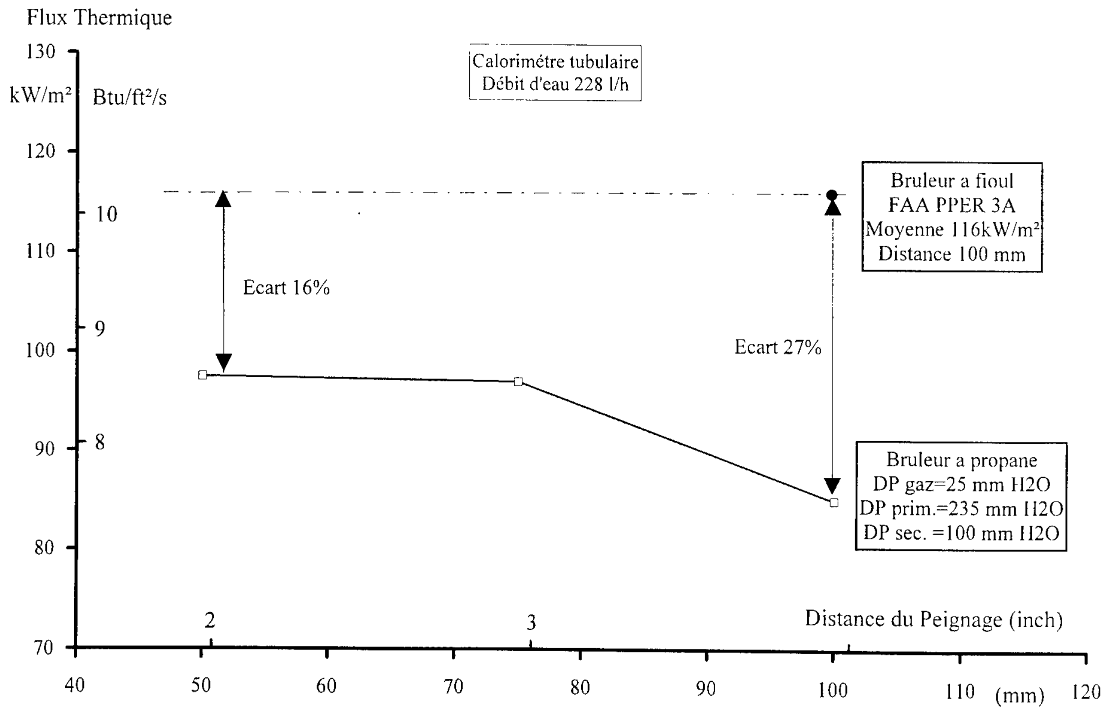
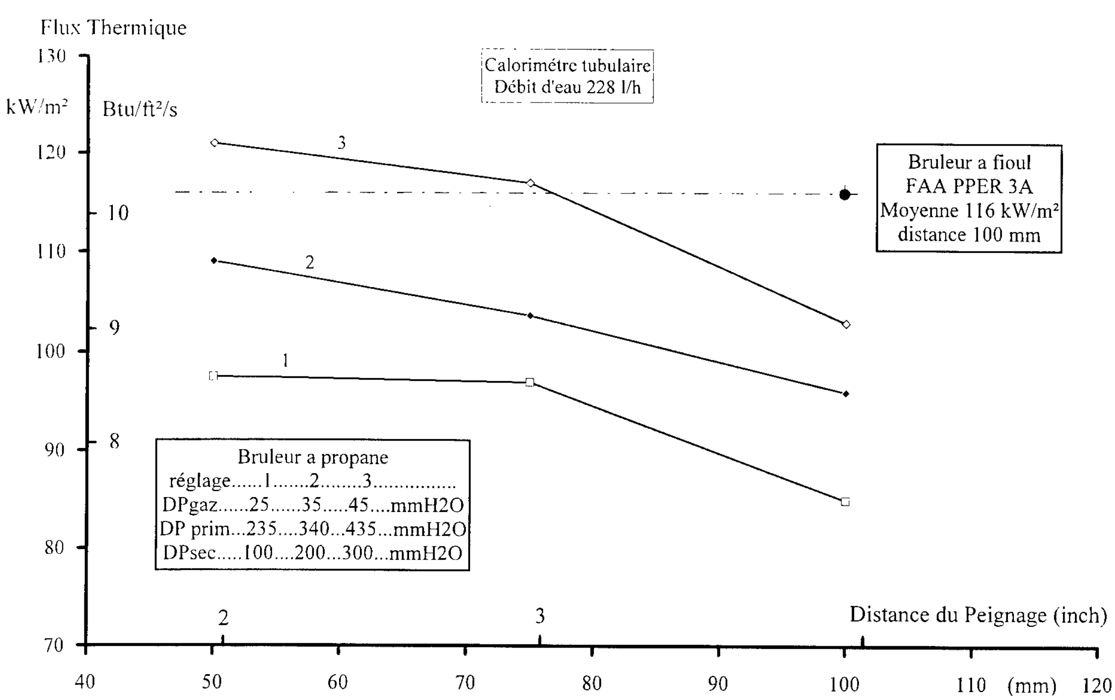


FIGURE 4



FLUX THERMIQUE DU BRULEUR A PROPANE AS 401B

FIGURE 5



REGLAGE DU FLUX THERMIQUE DU BRULEUR A PROPANE AS 401B

FIGURE 6

TEMPERATURES DU BRULEUR A PROPANE AS401B

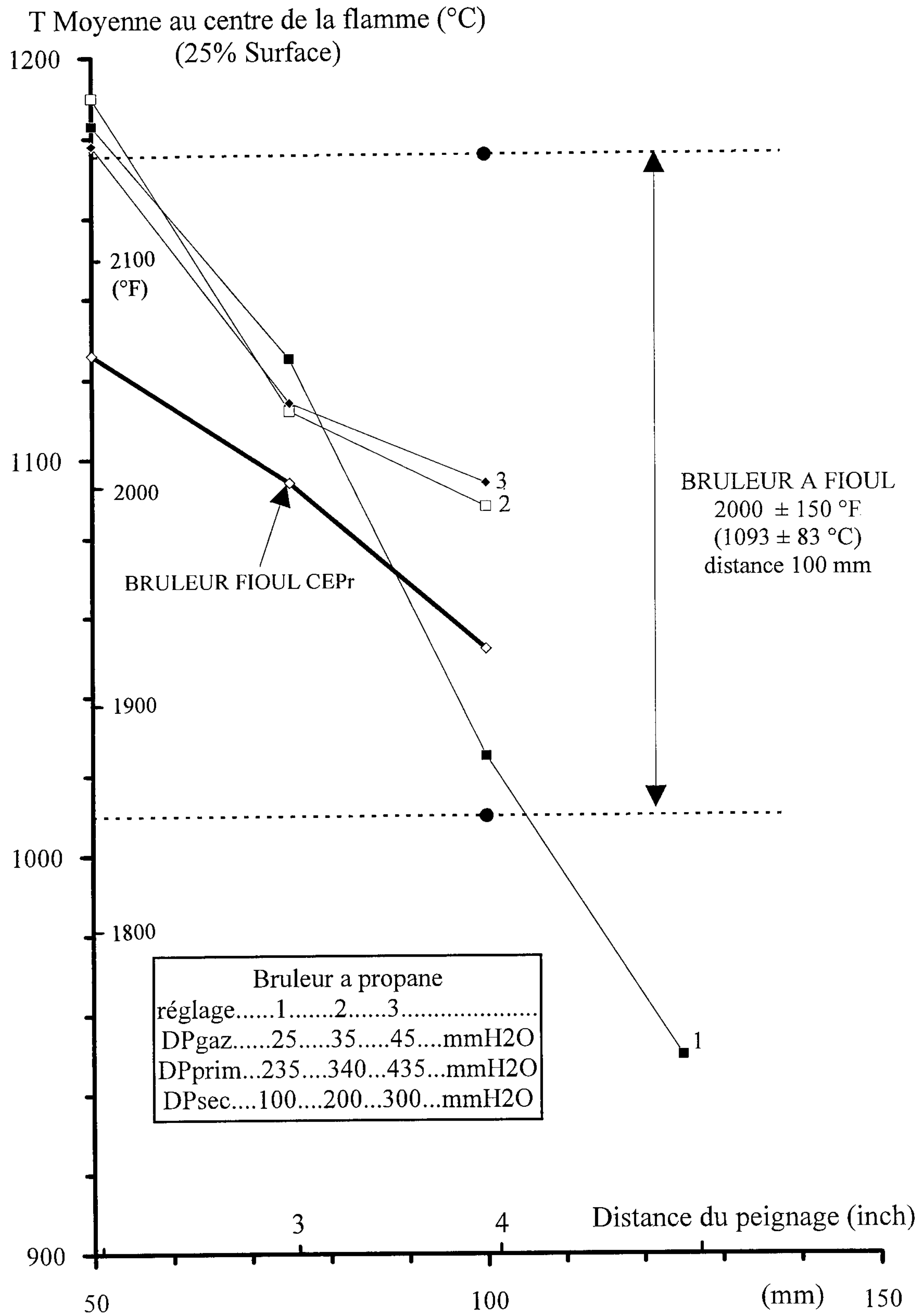
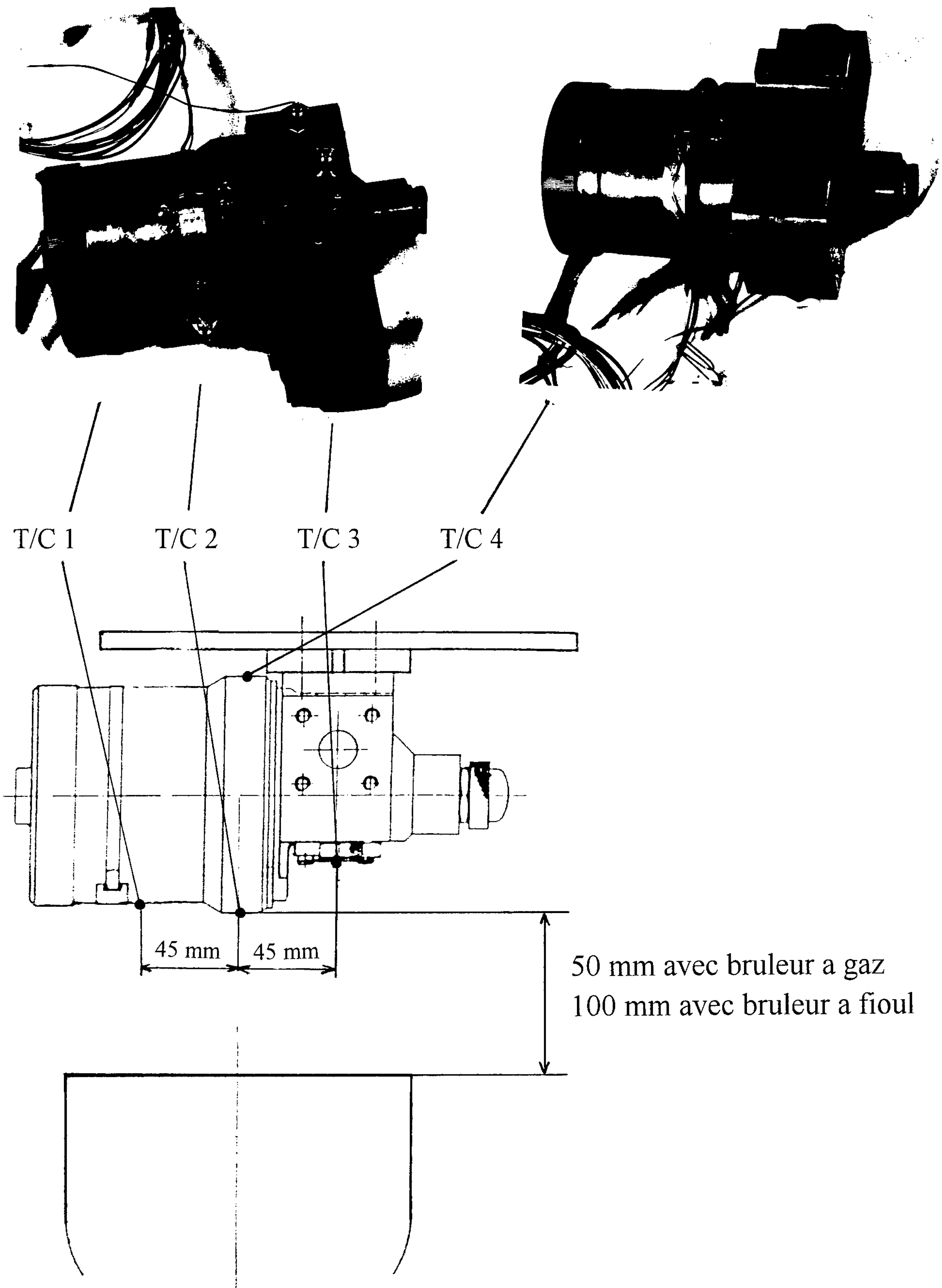
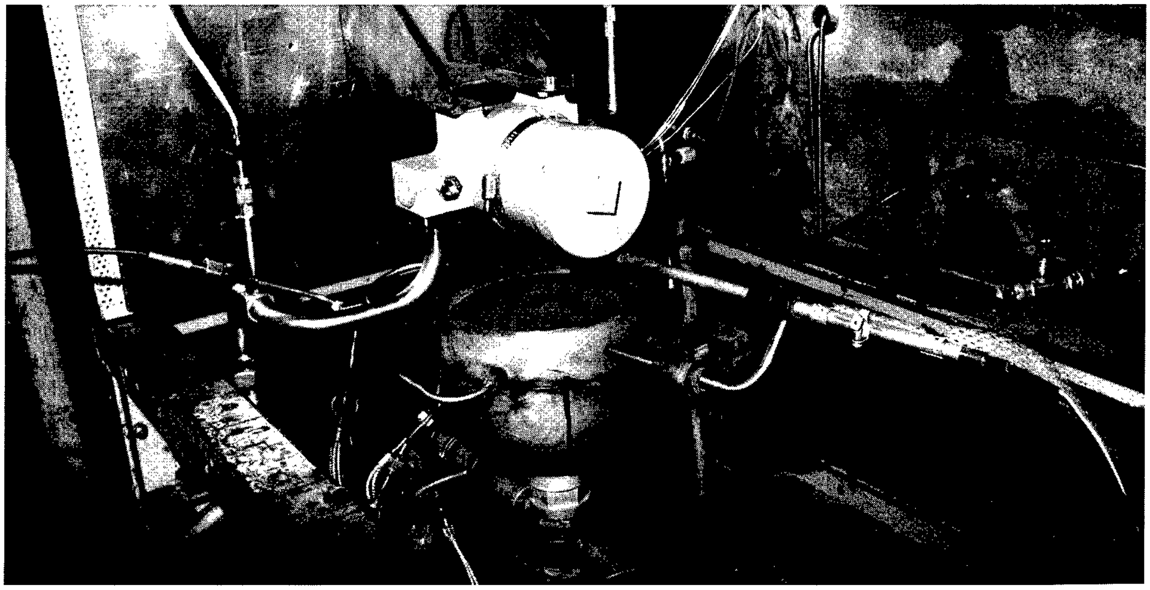


FIGURE 7

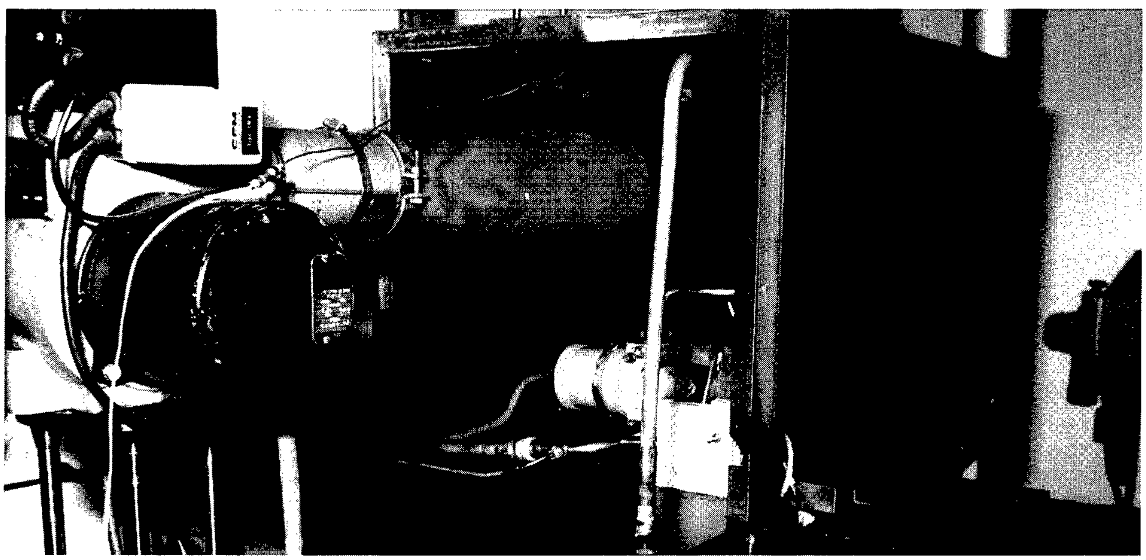


ESSAI AU FEU MODULE DE FILTRATION D'HUILE

FIGURE 8



ESSAI AU FEU AVEC BRULEUR A GAZ 161552



ESSAI AU FEU AVEC BRULEUR A FIOUL 851697

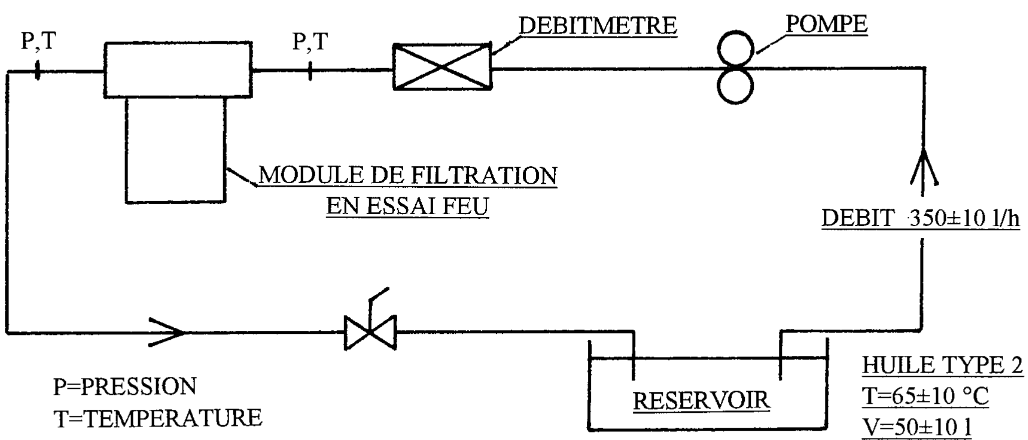


FIGURE 9

RELEVE DES TEMPERATURES T/C 1 A T/C 4

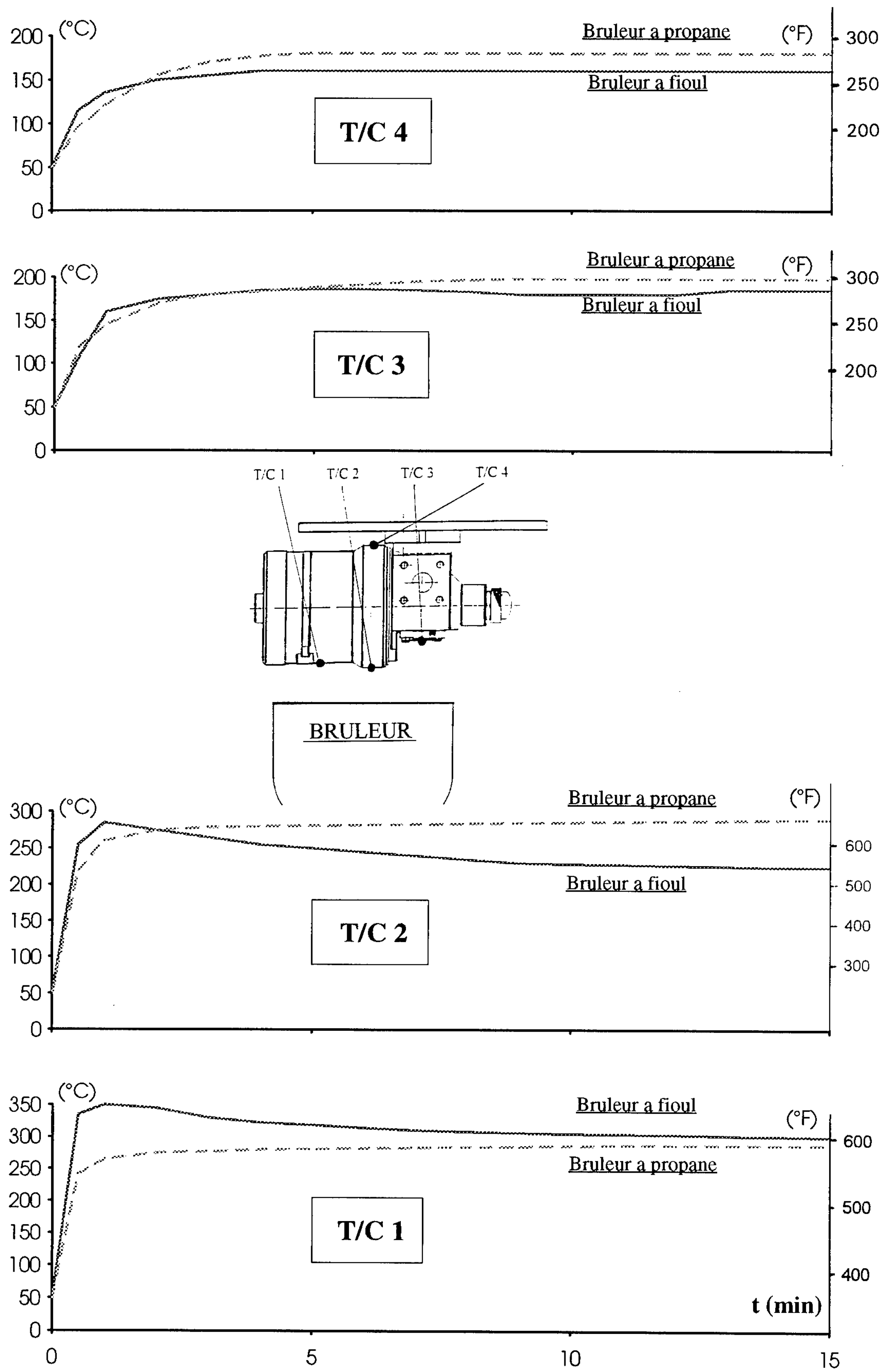


FIGURE 10

ESSAI AU FEU . CORRELATION CALCUL/ESSAI

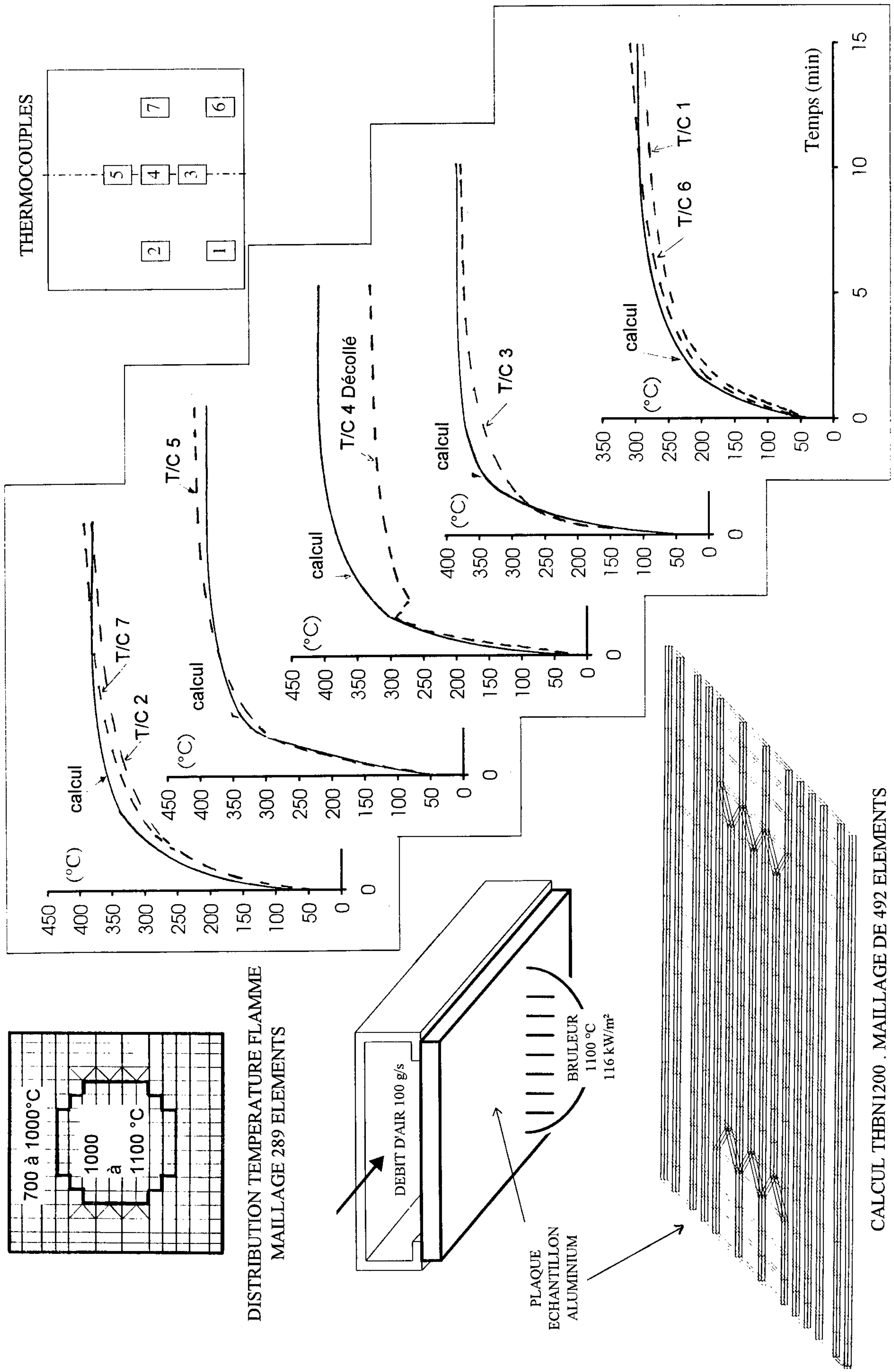


FIGURE 11

CORRELATION CALCUL/ESSAI SUR MODULE DE FILTRATION

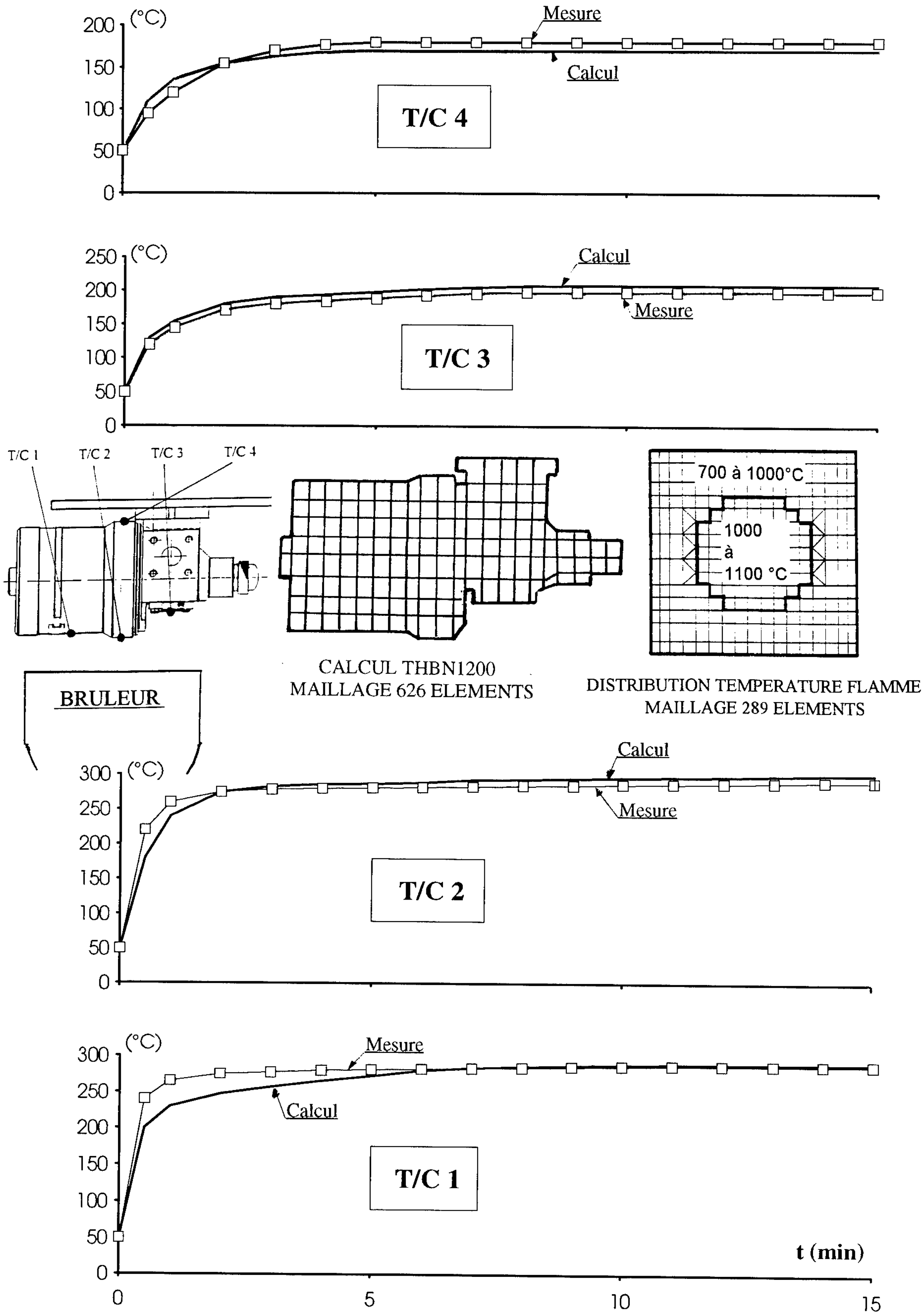


FIGURE 12

DISCUSSION - PAPER NO. 21

W.B. de Wolf (Question)

Looking at the axial and lateral temperature variations in your burner test flow, could you comment on how well these comply with the requirements specified for this type of testing? What was the flow velocity in the jet?

P. Derouet - Author/Speaker (Response)

In term of axial/radial temperature, the requirements are given in the Standards (ref. table 1 of my Paper):

- for the gas burner (ISO 2605), the temp. must be 1100°C ± 80°C on a surface ≥ 25% of the total surface.
- for the fuel burner (AS 1055/1377), the requirement is not the surface but only a line (axial along the length) 6 inches (or more) where the temp. must be ≥ 2000°F ± 150°F.
- my Paper gives, in fig. 3, an example of the axial/radial temp. distribution versus gas/fuel burner.
- the velocity of the flame (gas burner) is about ≈ 8m/s.

Thermal And Mechanical Loading On A Fire Protection Shield Due To A Combustor Burn-Through

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1. SUMMARY

A combustor burn-through can give rise to an under-expanded, sonic or supersonic jet of gases and flames out of the combustor. The pressure and temperature in the jet may be as high as the highest values of pressure and temperature arising in the combustor. In order to protect the engine and aircraft components from exposure to the jet over a period of time, a fire shield is installed adjoining the combustor. The United States Federal Aviation Administration has issued an Advisory Circular 20-135 redefining the requirements on the fire protection shield, and the overall objective of the project was to establish the basis for a preliminary design of a test facility and testing procedure for such fire shield materials. The current study was devoted to the determination of the mechanical and thermal loads that arise on the shield due to the impact of hot, high pressure, high speed jets. The results obtained assist in the identification of some of the essential features required in a test facility, and the test plans and procedures.

2. INTRODUCTION

In flight gas turbine combustors, a crack or opening in the combustor wall, which may be due to local heating and material failure, and therefore, often referred to as a burn-through, causes the high pressure and temperature gases within the chamber to escape in the form of a jet. On impact, the jet can cause extremely high heat transfer (accompanied by severe mechanical loads) to the impacted surface, and become a cause for fire. Depending on the installation of the engine, the impaction and the resulting fire can extend to the nacelle and the pylon, and, in rare cases, even to the wing. The jet and the resulting fire may also spread downstream along the engine. In all cases the effects are primarily dependent on the characteristics of the jet, namely the jet composition, pressure, temperature, and geometry of the wall opening.

In the worst condition, the pressure and temperature of the jet may be equal to the highest values of those quantities arising in the combustor; thus, the pressure may be 20 - 40 atmospheres in current engines, and the temperature may approach the adiabatic flame temperature of Jet A fuel, under near stoichiometric conditions. The size of the jet, which depends at its origin on the size and geometry of the opening in the combustor wall, is another parameter of importance. In practice, the size of the opening may be expected to be quite small at the time of wall failure, and then grow to some maximum size with a shape different from that at the beginning. The jet invariably is sonic or supersonic, depending on the nature of the combustor casing failure and the resulting geometry of the opening. For example, if the wall material at the opening 'petals' outward due to the local pressure difference across it, then a supersonic flow results due to the divergence of the opening. In all cases, it can be expected that there is substantial under-expansion in the jet at its origin, and therefore, the jet undergoes further expansion during its development. However, when the jet faces a surface, the flowfield development itself is affected by the separation distance of the impacted surface from the jet origin.

The jet may, in general, be chemically reactive, and often contain unburned fuel that is gradually undergoing reaction during jet development and accompanying entrainment of air. On impingement, it is possible for chemical reactions to occur on the impacted surface, assisted by the surface heating that increases due to both the jet impact and also the jump in temperature from the plate shock formed ahead of the jet fluid stagnation region. In practice, a common approach to the problem is to contain the fire to the vicinity of its source by means of a fire shield surrounding the combustor region. Ideally the fire shield should be capable of withstanding the mechanical and thermal loads imposed on it by the jet over a specified period of time without undergoing a failure and thereby causing a spread of fire to other parts. The chief interest in the current paper is in the mechanical and thermal loading generated on the fire shield under different conditions, a parameter of primary importance in the design and testing of a fire shield. It is noted that the fire shield under discussion here is different from firewalls currently installed to containing engine fires, which are regulated by well established standards.

In this regard, the United States Federal Aviation Administration has issued an Advisory Circular 20-135 concerning powerplant installation and propulsion system component fire protection methods, standards, and criteria [1]. Related FAR sections are given in Appendix I of the AC to provide guidance on demonstrating compliance with the FAR. The original fire protection methods were developed in the 1950's and the requirements for the installation of fire protection walls were specified in FAR 25. The 1990 Advisory Circular deals with protection against a more intense flame than previously specified, the so called standard flame. The more intense flame corresponds to a fire condition within the engine, which burns through the engine case, causing a high pressure, high temperature gas jet to escape. The pressure and temperature under consideration are 350-550 psi (2.4 - 3.8 MPa) and 3000 - 3500 °F (1650 - 1930 °C), respectively, with the test jet nozzle size specified as one inch diameter (25.4 mm). The location of the fire shield during a test is given as the distance of the fire shield from the combustor case as installed in practice. The duration of

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the exposure of the fire shield to the jet is also modified in the new advisory: the burn-through protection is required to withstand a minimum flame temperature of 3000 °F (1650 °C) at the impacted surface for a period of 3 minutes under peak pressure operation of the combustor. The specific emphasis on the temperature at the fire shield surface is due to the possible reduction in jet temperature over its traverse to the impacted surface. It is noted that the AC does not specify such other features as (a) the composition of the jet material, especially its content of unburned fuel or other chemically active substance, (b) the growth of the jet from a small to a large size as a function of time, and (c) the influence of a cross-flow, that may often be present in the region of jet flow or over the impacted plate. However, the AC also addresses other aspects of engine installation.

At this time, there are no standardized test facilities and specified test requirements for undertaking such tests with the new test conditions. A suitable facility must include (a) a high pressure, hot gas generator, (b) a structure for locating a part or a sample of the fire shield material with adequate strength and freedom from vibration and warping during jet impact, and (c) the required observational tools and rig safety devices. The test requirements must address in particular any conditions under which the magnitude and character of the mechanical and thermal loads become critically severe for the integrity of the fire shield.

It has been proposed by the FAA that a new test facility be developed, along with a test plan, so that fire shield materials and structures can be adequately tested and proved for satisfaction of the Advisory Circular. The design of a test facility and the establishment of standardized test plans and procedures is a complex task involving technical, safety, and other considerations, that require substantial technical effort, and considerable evolution before a fully operational facility and testing routine can become established.

As part of a project supported by the FAA through a grant to Purdue University, a three-phase plan was developed for addressing the preliminary design of a fire shield test facility and the development of associated test procedure: Phase I for the determination of the nature and types of mechanical and thermal loads that can arise during impact of high temperature, high pressure, high speed jets on a simple impingement plate; this includes the development of a suitable gas generator and a test installation; Phase 2 for addressing complexities in the loads due to variations in the shape and orientation of the impact plate, and due to the chemical state of the jet; and Phase 3 for the actual development of the test facility and evolution of acceptable test procedures. Presently, Phase 1 activity is completed.

3. BACKGROUND

It may be pointed out at the outset that the currently reported investigation does not address the following issues: (a) the circumstances and causes that lead to the occurrence of a combustor (and engine case) burn-through; (b) the problem of detection of the presence of a hot gas (or flame) jet in the vicinity of a combustor, or of overheating or a flame at the fire shield; and (c) the materials utilized in the design and manufacture of a fire shield, that can become ignited at the temperatures of interest (for example, columbium), or that may become too heavy in providing the required structural integrity (for example, combinations of titanium, stainless steel, and insulation such as refrasil). These are extremely important issues of great current interest. Thus the current paper is devoted solely to the experimental investigations on the jet impingement processes following combustor burn-through. Other engineering contexts in which high speed jet impingement is significant are in thrust reversers, vertical lift generation, rocket-assisted landing, stagnation flow on leading edges, heating and cooling schemes, and certain manufacturing processes.

The FAA undertook some early tests [2-5] on jet impingement caused by combustor burn-through. The main concerns in the test program were (a) the method of simulating the jet resulting from combustor burn-through while ensuring the temperature and heat flux at the impacted surface, (b) the thermal loading caused by the jet impact on a plate representing a test article such as a fire shield, and (c) the establishment of jet exposure time under different conditions for the occurrence of a burn-through on various shield materials. Several options were tested for generating the hot gas jet, and a can burner with a hole in the blocking plate was established as satisfactory for generating hot gas (or flame) jets of required characteristics. The loading generated by the jet at the impingement location on a plate was established by measurement of pressure and temperature at the plate when separated by various distances from the combustor opening, which was varied from 0.25 - 2.0 inches (6 - 50 mm) in different tests. Typical observed temperature and pressure data are presented in Table I and Figs. 1a and 1b respectively. The early work also included tests with flat plates located at different orientations with respect to the jet axis, and plates with curvature. The data from these tests pointed to a need for more extensive investigations, and also became the basis for the AC issued later.

A basic schematic of the jet impingement flow conditions and structure is provided in Fig. 2. As can be seen, the nature of the high speed jet impingement is complicated in several respects: the initial development of the under-expanded jet, the jet development in the region of interaction with the impingement surface, and the spread of the jet over the surface. Several regimes of flow can be identified corresponding to different jet conditions and plate locations, with some similarity in selected features (including distribution of loading) in each regime.

Aside from the work of Gardon and Coponpue [6], and more recently Fox et al. [7,8] and Lee et al. [9], high speed jet impingement heat transfer has not been examined in depth. However, there exists much more information regarding the dynamics of a jet and impingement flow field, including surface pressure loads. Both Donaldson and Snedeker [10] and Iwamoto [11] have found that scaling of the impingement characteristics with respect to free jet

characteristics can be helpful, particularly in regard to the influence of the location of the impingement plate in a region of jet expansion or compression. A number of studies by Hunt and coworkers [12-14] present the surface pressure distribution for a variety of impingement conditions, and Cobbald [15] has considered the surface pressure distribution due to very high pressure ratio jet conditions. In general, two regimes of flow have been observed: one in which the peak pressure arises at the geometric center of impingement, and the other in which a stagnation bubble appears above the plate, with the peak pressure occurring over a ring of finite radius around the center of impingement. The stagnation bubble is a region of trapped air that recirculates due to the annular slip line shear layer that helps to contain the bubble. Ginzburg et al. [16] hypothesize that the slip line shear layer formed by the shock triple point of the plate shock and inner jet shock serves to separate the wall boundary layer and create the stagnation bubble region. The presence of a stagnation bubble is found to create a region of high pressure over a larger surface area than for typical stagnation point flow. At sufficiently high pressures, the wall jet displays a series of reflected shock waves. None of these studies, however, measured surface temperature in the presence of a stagnation bubble and do not, for example, indicate the formation of an annular region of peak temperature on the surface. These conditions also lead to expansions strong enough to accelerate the flow in the vicinity of the impingement point to supersonic Mach numbers in the wall jet, resulting in shock rings. These shock rings create regions of rapidly varying temperature and pressure along the radial direction over the plate, with potential for large gradients and associated stresses.

Recently, a number of computational studies of the supersonic jet impingement process have been published, see Tsuboi et al. [17], Kim and Chang [18-19], and Hong and Jeon [20]. The impinging flow presents a formidable challenge to CFD, with numerous shocks, shock-shock interactions, and shock-shear layer interactions; nevertheless, recent results are illuminating. Tsuboi et al. [17], Kim and Chang [18] have studied the three dimensional problem of inviscid jet impingement on an inclined plate, and compared predictions with the surface pressure measurements of Lamont and Hunt [13]. Furthermore, they indicate an interesting azimuthal pattern of fast and slow streams in the surface velocity vectors. While the simulation is inviscid, if the pattern is taken as representative of some plane near the wall boundary, the expectation would be to see associated variations in the surface temperature due to convection. Similar patterns have been observed by Yokobori et al. [21] in low speed jet impingement and have been attributed to localized enhancement of convective heat transfer due to the presence of streamwise vorticity in the developing region of the jet. Kim and Chang [19] have also considered the normal impingement of an inviscid, axisymmetric jet with nonequilibrium air properties. They demonstrate the possibility that variable thermal properties may have a significant influence on the structure of the jet flow, particularly in the flow region between the plate shock and the surface. Hong and Jeon [20] have developed a 3D Navier-Stokes solver for the case of jet impact on a flat plate, and this holds some promise for the future. It is noted here that in current practice, the ability of the fire shield to withstand the jet loads is often demonstrated through numerically predicted loads. However, calculations at less than the Navier-Stokes level can not be trusted to yield all of the complex loads and their distributions.

For high speed jet impingement heat transfer, the jet flow shock structure is important, and several recent works also indicate that unsteady flow processes can also arise and significantly alter the surface heat transfer characteristics. Fox et al. [7] considered a high subsonic jet (M=0.9) and proposed that a local separation of stagnation temperature occurs due to the unsteady pressure field associated with the passage of coherent vortex structures in the jet. This concept was called 'vortex-induced total temperature separation.' This is different from the 'shock-induced total temperature separation' mechanism under supersonic flow conditions recently proposed by Fox and Kurosaka [8] to explain observations of localized cooling in supersonic jet temperature distributions. The vortex-induced separation seems to explain both peaks and valleys in the radial distribution of total temperature in subsonic jets in both the near- and farfield. Goldstein et al. [22] suggested that the local cooling found in low speed jet impingement at small plate separation distances is the result of annular vortex ring-induced energy separation while Yokobori et al. [21] proposed streamwise vorticity. Meola et al. [23] have also recently found that large scale recirculations formed in the jet impingement process may explain the secondary peak in heat transfer coefficient observed in close impingement. Clearly, unsteady vortical motions can have a significant influence on impingement heat transfer; yet there is not a consensus on the underlying mechanism responsible for these effects. The current experimental results do indicate that it is possible under supersonic flow conditions to establish regions on the surface that are hotter or cooler than the jet stagnation temperature, which may be of significance in identifying specific jet impingement conditions for testing fire shields.

In summary, from the point of view of testing fire shield materials and structures, there are considerable ambiguities in regard to the following: a) the regimes or groups of conditions that characterize the changes in the impingement loading; b) the scaling of the flowfield features and the impingement loading as a function of the jet and impingement parameters; c) the influence of chemical reaction and burning in the jet and at the impacted plate, including catalytic effects on the surface; and d) the scaling of the impingement loading as a function of time during which there may be changes in jet initial conditions, size of the jet, and the nature of the impacted surface. The current paper addresses only the first two aspects, and the associated experimental studies.

4. EXPERIMENTAL FACILITIES

The research centered around two test rigs, one referred to as the Main Facility (MTF) and the other referred to as the Auxiliary Test Facility (ATF). The MTF had a wider range of operating conditions than the ATF, including vitiated or non-vitiated high temperature flow at high pressures. The ATF was smaller in size, but the facility has access to a more extensive array of flow diagnostics. Numerous measurements were made of surface pressure, temperature and heat flux on the impingement plate for a variety of jet conditions and plate separation distances in both rigs. Key parameters of the two test rigs are outlined in Table II, and described in further detail by Stuerman [24] and Love [25].

While both rigs could operate with either a sonic nozzle (convergent nozzle, M=1.0) or a supersonic nozzle (convergent-divergent nozzle, M=1.5), in the MTF the stagnation temperature of air in the low temperature regime of jet operation was raised by mixing cold air with combustion products from a gas-fed heater. For the high temperature regime, a dedicated high pressure combustor was utilized to provide the jet fluid. In the ATF, the air supply was heated to about 40 °C using strip heaters.

In the ATF, the low stagnation temperature allows advanced diagnostics to be used. These included dynamic response temperature sensitive fluorescent paints as well as schlieren and planar Mie scattering flow visualization techniques to study the jet shock and vortex structure. Flow visualization using laser sheet Mie scattering and schlieren photography is used in both a qualitative and quantitative manner. Schlieren photography and stagnation pressure measurements provide information regarding the mean jet shock structure and the jet potential core length. The vortex structure is thought to play a key roll in the observed surface temperature patterns and time resolved snapshots of the jet vortex structure were obtained using a pulse laser Mie scattering visualization. Surface temperature measurements were conducted using the temperature sensitive fluorescent paint EuTTA (Europium Thenoyltrifluoroacetonate). A video camera was used to record the fluorescent paint response over the desired impingement area. EuTTA has an inverse intensity response as a function of temperature, which when calibrated allows conversion of intensity images to surface temperature maps. Since the ATF impingement plate is water cooled, the surface temperature distribution is directly proportional to the local heat flux distribution. The spatial resolution of the technique was found to be very good, although dependent on the optical magnification and video camera array resolution. However, use of the paint does place a restriction on the maximum allowable jet temperature to about 50°C.

In the MTF rig, 60 type K thermocouples were embedded in the front surface, the plate thickness and on the back surface. Also, 14 surface pressure taps were arranged in a cross on the test plate. Schlieren pictures of the flowfield were obtained in most of the regimes of test operation.

5. TEST PLAN AND CONDITIONS

A considerable amount of diagnostic testing was carried out, initially and throughout the test program. A summary of the tests conducted is provided in Table III. A number of additional tests were carried out when it was felt that the flowfield or the impacted plate processes showed an interesting feature. In particular the ATF was used to study the jet structure in greater detail, with emphasis on the impingement shock structure relative to the shock structure of a free jet. These studies were confined to the near field of the jet, with the location of the impact plate within the jet potential core, or slightly beyond it. In some of the tests, the length of the jet potential core was also measured. Other cases that demanded more in-depth study included conditions leading to the formation of a stagnation bubble, as well as conditions that were observed to give rise to stagnation temperatures at the impingement surface apparently higher than the jet stagnation temperature, an unresolved issue to date as stated earlier.

6. RESULTS

The test results may be considered under three groups: 1) the mechanical pressure loads generated on the plate, 2) the thermal loads generated on the plate, in the axial and radial directions, and 3) the structure of the jet both in terms of initial jet development and also in terms of the jet shock structure in the vicinity of the impact plate.

6.1. Surface Pressure Measurements

The mechanical loading on the impact plate can be evaluated from the surface pressure distributions. Figure 3 shows a series of surface pressure distributions at different operating pressure ratios (Pr) from a supersonic nozzle. The transition between a stagnation point-type distribution (Pr=5.0 and 5.5 in Fig. 3) and a stagnation bubble-type distribution (Pr≥6) is clearly observed. Also, as the pressure ratio increases, radially varying pressure fields are established outside of the stagnation ring, indicating the likely presence of annular shocks. The occurrence of this variation seems to be most apparent for moderate pressure ratios, which also correspond to the appearance of the stagnation bubble flow. It might be expected that the mechanical loading of a jet from a supersonic nozzle would be greater than for a sonic nozzle at the same jet pressure ratio, due to the reduced shock losses in the supersonic jet. However, the influence of the impingement distance relative to the length of the jet shock cell (which is dependent on the jet Mach number) and the strength of the plate shock complicate the assessment of mechanical loading.

On an overall basis, the pressure distribution on the plate can be integrated to estimate the total force exerted on the plate by the jet as a function of the jet pressure ratio. The results are shown in Fig. 4 for the convergent nozzle case at three different distances, and in Fig. 5 for the convergent-divergent (CD) nozzle case at the same distances. The CD nozzle case shows a relatively self-similar loading of the plate as a function of pressure for impingement between three and eight jet diameters. This response is also quite similar to the farfield loading (z/d=8)

of the sonic nozzle. The deviation observed for close impingement occurs for nozzle pressure ratios known to generate Mach disks at the end of the first shock cell [26] and are seen to generate a stagnation bubble on the plate. (Mach disks are normal or near-normal shocks that form in various supersonic flows when oblique shocks cannot satisfy local pressure and flow turning boundary conditions.) It is believed that at these close impingement distances, the plate shock couples with the naturally occurring Mach disk of the first jet shock cell and leads to elevated pressures in the stagnation region. Since the CD nozzle flow weakens or eliminates the natural formation of a Mach disk for the same pressure ratios, no such coupling is clearly observed. With increased pressure ratio the shock cells enlarge and are expected to eventually couple a Mach disk to the plate.

Figure 6 shows the maximum pressure on the impingement surface versus the jet pressure ratio. The maximum plate pressure is expressed in dimensionless form as the maximum dynamic pressure recovered on the plate normalized by the dynamic pressure at the nozzle exit, $(P_{pmax} - P_e)/(P_{tj} - P_e)$, where P_e is the static pressure at the nozzle exit. This parameter gives some indication of the combination of plate shock strength and recovered pressure at the plate. At high pressure ratios, the plate shock is so strong that nearly the entire dynamic pressure available at the nozzle exit for recovery is lost, and the pressure load on the plate is smaller. At the very low pressure ratios, the plate shock is weakest, so that total pressure losses are minimal, and it is possible to recover most of the initial dynamic pressure on the surface, with correspondingly large pressure load on the plate. An interesting region occurs, for the convergent nozzle, in the pressure ratio range from 4 to 8 (coinciding with the observed increased loading of the plate seen in Fig. 4), where secondary peaks in the pressure recovery occur. The explicit relationship between the total loading on the plate and possible coupling of the jet shock cell with the plate shock is at present not fully understood and requires further study. However, for the combustor burn-through scenario, surface pressure gradients at these conditions are critical when coupled with thermal gradients in the same regions of the impact plate.

6.2. Surface Temperature Measurements

Surface temperature measurements from the MTF impact plate are shown in Figs. 7 and 8 for impingement from a sonic and supersonic nozzle, respectively. At close impingement, (Fig. 7), the temperature distribution for Pr=7.8 indicates that the peak temperatures occur not at the centerline, but at a radius of about one jet diameter, consistent with the surface pressure (Fig. 3) distribution that showed a stagnation bubble. The existence of the stagnation bubble at this condition is not as clearly indicated by the surface temperature as by the surface pressures, and this is due to the fact that the MTF impingement plate is designed to simulate the response of an actual fire shield, and does not have a controlled thermal boundary condition on the rear of the plate. Thus, the surface temperature distribution is smeared somewhat due to conduction in the plate and to non-uniform rear surface boundary conditions. These effects are primarily located at the central impingement region, so that while other conditions may actually indicate a stagnation bubble flow, the MTF surface temperature distributions are not the best indicators of their presence. Figures 7 and 8 show that increasing jet pressure ratio leads to increased plate temperatures, except for the central temperature reduction in the case of a stagnation bubble. Despite the central cooling provided by the recirculating flow in the stagnation bubble, the surface temperatures are elevated in the region outside the stagnation bubble. The freely variable temperature condition on the back side of the MTF plate leads to a concentration of heat in the center of the plate with radial outflow due to heat conduction to the lower temperature regions, and, along with the effects of flow processes such as annular shocks and elevated annular pressures for stagnation bubbles, the redistribution of heat results in a peak heat flux at about r/d=2 from the center of impingement. In addition, the combination of the thermal stresses at these radial locations may couple with the peak mechanical loads of a stagnation bubble flow to lead to a potentially critical condition for failure of a fire shield.

In the ATF, the use of dynamic response temperature sensitive fluorescent paints and a water bath-cooled impingement plate permit a better assessment of the direct influence of flow processes on the surface conditions. Since the response of EuTTA is inversely proportional to the local temperature, high temperature regions appear dark relative to low temperature regions. This is seen in the surface temperature images shown in Fig. 9. Both Fig. 9a and 9b, for Pr=4.5 and 6.0 respectively, correspond to the impingement of a supersonic nozzle at z/d=4. The flow for Pr=4.5 exhibits a stagnation point flow condition, while the Pr=6.0 flow indicates the formation of a stagnation bubble with two annular shock rings. Of note is the broader region of higher surface temperature (dark) for Pr=4.5. For Pr=6.0 the warm regions are confined to the stagnation bubble in the center of the plate and thin annular rings that are assumed to coincide with the reflection of oblique shocks off of the surface in the wall jet flow [12]. Fig. 10 is a compilation of a number of surface temperature data sets at z/d=8 and for pressure ratios from 2 to 6, all for a supersonic nozzle. Shown is the radial variation of the difference between the surface temperature and the ambient temperature normalized by the difference between the jet stagnation temperature and the ambient temperature, $(T_p - T_a)/(T_{tj} - T_a)$. The jet stagnation temperature was 40 °C, near the 'turn-off' temperature of the paint and the ambient temperature was nominally 15 °C. Pressure ratios from about 3.0 to 5.5 indicate higher peak temperatures than for other jet pressures. When the impingement surface is brought closer to the nozzle, z/d=4, the surface temperature distributions for pressure ratios from 3 to 6 all exhibit lower peak temperatures, as illustrated in Fig. 11. The traces for Pr=4.5 and Pr=6.0 in Fig. 11 correspond to the images shown in Fig. 9a and 9b, respectively. It is often easier to detect the incipient stagnation bubble development from the temperature traces rather than from the images directly, as is the case for Pr=6

above, although, in other cases where the bubble is well defined, the images generally suffice. The presence of annular rings in the temperature profiles typically coincide with the presence of a stagnation bubble; however, annular rings may also appear as precursors to the formation of a stagnation bubble. Similar features were observed in the surface pressure traces in Fig. 3.

6.3. Jet Structure

It is clear that the mechanical and thermal loads due to jet impingement are a function of jet pressure ratio, the type of nozzle (convergent or CD), and the separation distance between the jet exit and the impacted surface. Numerous length scales and time scales associated with these parameters can be developed. For instance, Love et al. [26] have compiled substantial data regarding the characteristic shock cell length scales for a number of nozzle Mach numbers and a wide range of pressure ratios, including the shock cell length, the centerline length for either a regular or Mach reflection, and the diameter of a Mach disk (when present). An additional length scale is the jet potential core length, which is an indicator of the transition of jet flow to the fully developed, farfield jet flow. In the current investigation, the basic character of the free jet shock structure and the jet potential core length were obtained from schlieren imaging. Also, centerline traces of the jet stagnation pressure were obtained with a traversing total pressure probe. Characteristic total pressure traces along the jet centerline are shown in Fig. 12 for several jet pressure ratios from a sonic nozzle. For the sonic nozzle, a jet pressure ratio greater than approximately 3.8 will lead to the formation of a Mach disk at the end of the first shock cell. This is noted by the extended low total pressure reading following the initial jet expansion. As the inner subsonic jet behind the Mach disk mixes with the outer supersonic jet flow, the total pressure rises and exhibits the characteristic shock cell structure until significant mixing with the ambient fluid reduces the jet total pressure. These plots can be used to obtain an estimate of the length of the potential core of the free jet and to examine what type of free jet flow condition would naturally exist at a given location of the impingement plate. Figure 12 also supports the impingement surface pressures shown in Fig. 6, where moderate range pressure ratio jets are seen to recover a significantly greater portion of the initial dynamic pressure than much higher pressure ratio jets.

The variations noted in Fig. 6 are related to the local position of the impingement plate relative to the jet shock structure. This is more clearly seen by considering the height of the plate shock above the surface as a function of both jet pressure ratio and impingement distance. The location of the plate shock was estimated using schlieren photography, as shown in Fig. 13a and 13b for jet impingement at z/d=4 and for Pr=4.5 and 6.0, respectively. These are the same conditions as for the surface temperature images in Fig. 9. Significant differences in the jet structure and the resultant surface flow in the near field of impingement can be seen in different cases. From a large set of video data, the location of the plate shock is estimated as the impingement distance is varied with a constant jet pressure ratio. Figure 14 shows these estimates for a Pr=4 sonic jet compared to the free jet shock structure, and Fig. 15 shows the same type of comparison for a Pr=6 jet. The plate shock location is seen to correlate well with the free jet shock structure. Higher jet pressure ratios create a stronger initial Mach disk, and as seen in Fig. 15, this can lead to an extended region where the shock is in a relatively constant location above the impact surface. In contrast, the shock location is seen to 'cycle' with the plate location in the weaker shock cell regions. This means that relative to the jet shock cell, the plate shock tends to get 'locked' into a favored position within the shock cell until it becomes unstable and 'hops' to the next cell. Such hops are readily visible when conducting experiments with the temperature sensitive paints and are often accompanied by significant changes in the surface temperature distribution.

7. DISCUSSION

Based on the background studies and the current investigation, three possible failure modes are hypothesized for a fire shield experiencing jet impingement from a combustor burn-through: 1) elevated surface temperatures exceeding the limits for the plate material, 2) steep gradients in the surface temperature leading to severe internal thermal stresses in the material, and 3) the potentially severe mechanical stresses in the material imposed by the pressure force of the impinging jet, in conjunction with reduced structural strength at high temperatures. Accordingly, experiments have been focused on determining jet conditions that produce those modes. In summary, no single condition has been found that produces a clearly worst case heat transfer scenario. However, various regimes of magnitude and distribution of thermal and mechanical loads have been identified that may be utilized in generating a test plan for proof testing a fire shield material.

In terms of the jet structure, a major finding for isothermal and slightly heated jets is the observation of peak surface temperatures consistently greater than the jet stagnation temperature when the impact plate was placed at a distance corresponding to 75% to 100% of the free jet potential core length, as shown in Fig. 16 for results from both sonic and supersonic nozzles. Those results implicitly include the influence of the jet Mach number and pressure ratio, since the potential core length of a given jet is dependent on these parameters. They suggest that, for any desired jet pressure ratio and Mach number, a placement of the impact plate near the tip of the jet potential core causes the highest possible surface temperatures to be generated. At distances corresponding to the end of the jet potential core, however, the temperature distributions are typically quite broad. At closer impingement distances, lower central temperatures are observed, and steep temperature gradients due to shock processes in the wall jet region begin to appear. A stagnation bubble type of flow, which generally forms at high jet pressure ratios, close impingement, or combinations of the two, was also found to produce steep temperature gradients along the wall; however, the peak surface temperatures were generally lower than for

stagnation point flow. As a general rule, higher jet pressure ratios create stagnation bubble flows and the steepest temperature gradients along the wall, and as the plate distance from the nozzle exit is increased, so too the minimum pressure ratio necessary for a stagnation bubble to form also increases.

It is important to note that consistent results have been obtained with the MTF large jet and the ATF small jet. This suggests that over the range of conditions studied here, the absolute size of the jet opening does not have a significant effect, but must be considered in conjunction with other relevant length scales of the jet impingement process.

8. CONCLUSIONS

Considering the testing of a fire shield for its strength and structural integrity in case of a fire, it has been shown that a well-controlled hot gas facility is a necessity, and a high pressure combustor burning aviation gas turbine fuel can be designed and set up to meet the need. The test facility itself should be designed such that the fire shield under test can be located in front of the facility combustor nozzle and subjected to a number of hot jet exposures at various distances. While the testing may only be carried out with a part of the fire shield, the test article size must be compatible with the nozzle size as well as the physical dimensions involved in the configuration. The edge conditions of the test article become particularly significant in the test facility.

Under such a set conditions, the mechanical and thermal loads imposed on the fire shield are of particular interest in the regimes identified in the current study. The jet impingement experiments suggest specific failure modes that include peak surface temperatures possibly exceeding the jet stagnation temperature, induced thermal stresses from steep, radial temperature gradients on the surface, mechanical stresses from the impact pressure loading, or combinations of the above. It is then of importance to ensure that the test plan includes all those jet conditions under which the loads and their gradients are high, and also display special features such as a ring-type, or a radially varying-type distribution.

A set of simple tests under arbitrarily fixed sets of jet geometry and operating conditions cannot be adequate to provide the required proof of reliability and safety. Recommended specific conditions for testing are:

A) ***Highest operating pressure ratio of combustor, with a jet to plate separation dictated by the installation distance.*** This condition will vary depending on engine size and compression ratio, but it is expected to generate a stagnation bubble, annular shock rings, and a reasonably high bubble temperature.

B) ***Moderate pressures ($4 \leq Pr \leq 8$) and moderate plate distances ($4 \leq z/d \leq 8$).*** This region encompasses the stagnation bubble formation conditions with high values of precursor pressures and temperatures and annular shock rings, and potentially severe coupling of axial and radial thermal stresses with annular pressure loading.

C) ***Moderate pressures ($3 \leq Pr \leq 8$) and plate distances roughly 75% of the jet potential core length.*** These conditions correspond to stagnation point flow and the maximum observed temperatures on the plate, with relatively high jet pressure ratios. These conditions may also be considered as precursors to the stagnation bubble formation, with a slightly lower pressure ratio and/or slightly longer plate distance. The potential core length varies with jet pressure ratio and nozzle design, but generally follows the trends in Fig. 12, where for Pr=3 the core length is about 5-7 z/d, increasing to 12-16 z/d for Pr=6.

Even considering this one aspect of the overall problem, much still needs to be understood and quantified, for example, on the effects of time-dependent growth of burn-through hole (although the time to enlarge the jet opening may be sufficiently short as to make the final jet size the most relevant), flame jet conditions with unburned fuel, and complex fire shield geometry and structure. Confidence in numerical prediction schemes will grow as data from such measurements accumulate and clarify the physical mechanisms.

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Table I. Observed and Estimated Temperatures. Taken From References [2-5]

Pressure Ratio	Hole Diameter [inches]	Flame Velocity at Exit [ft/s]	Estimated Flame Temperature [°F]	Distance for 2500 °F [inches]	Distance for 2000 °F [inches]
4.0	2.0	2890	3700		
	1.5	2890	3700		
	1.0	2890	3700	~8.0	~10.0
6.0	1.0	2930	3800	~9.0	~11.0
9.0	1.0	3000	4000	~11.0	~15.0
11.0	1.0	3040	4100	~15.0	
16.0				36-40	42-46
20.0				44-50	53-59
25.0				56-62	68-74

Table II. Key Features of the Main Test Facility and the Auxiliary Test Facility

Parameters	ATF	MTF	Notes
Pressure, MPa	0.15-0.83	0.50-2.07	
Temperature, °C	15-40	100-350 700-1500	heater in MTF combustor in MTF
Nozzle exit diameter, mm	6.35	25.4	
Impingement plate distance / nozzle diameter	0-100	3-30	
Nozzle Mach number	1.0-1.5	1.0-1.5	
Nozzle Reynolds number x 10^{-5}	0.23-6.40	4.5-8.5	

Table III. Experimental Conditions

Convergent Nozzle			Convergent-Divergent Nozzle		
Pressure Ratio	z/d	Ttj/Ta	Pressure Ratio	z/d	Ttj/Ta
2	3, 4, 6, 8	1. 1.6 - 1.7	3.5	2, 3, 4, 6, 8	1, 1.06, 1.2 - 1.9
2.5	3, 4, 6	1, 1.6 - 1.7	4.5	2, 3, 4, 6, 8	1, 1.06, 1.2 - 2
3.5	3, 4, 6, 8	1, 1.8 - 2	4, 5	2, 3, 4, 6, 8	1, 1.06
4.5	3, 4, 6, 8	1, 1.8 - 2	2, 2.5, 3, 5.5, 6	3, 4, 6, 8	1, 1.06
3, 4, 5, 5.5	3, 4, 6	1	7.8	3, 6, 8	1, 1.1 - 2
7.8	3, 8	1.9	10, 12, 14, 16	3, 8	1

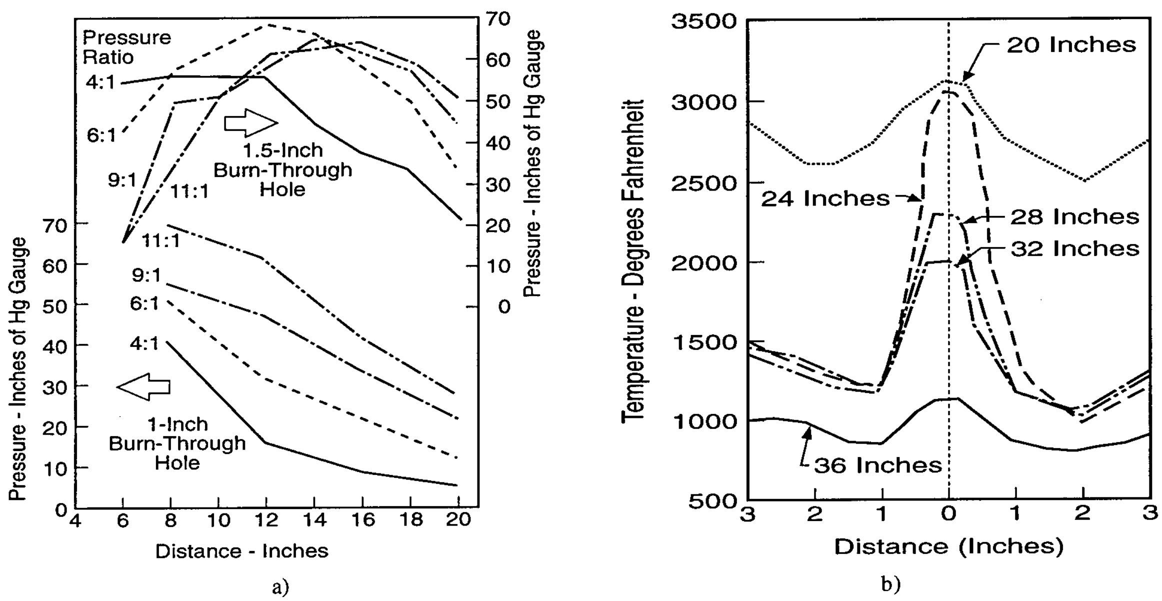


Figure 1. Results From Earlier FAA Studies of Hot Jet Impingement; a) Surface Pressures and b) Surface Temperatures. Redrawn From References [2-5].

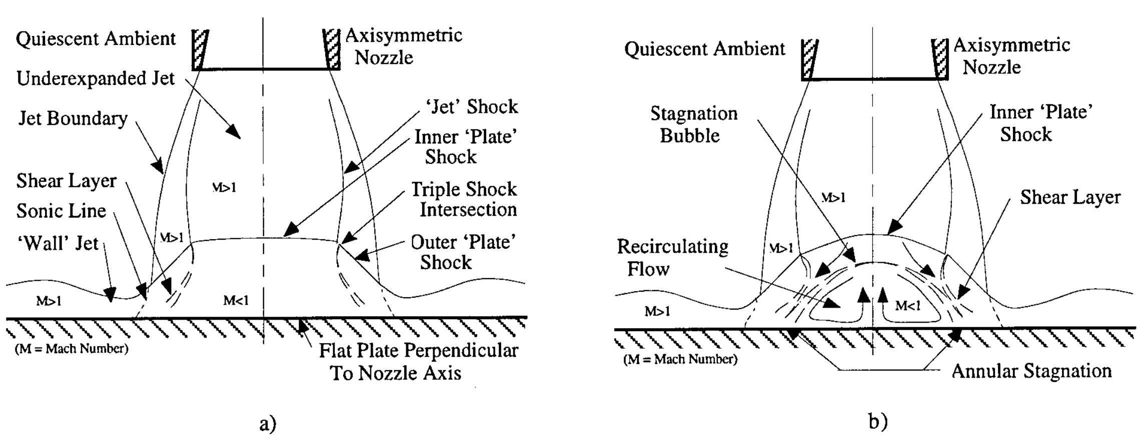


Figure 2. Schematic of Underexpanded Jet Impingement; a) Basic Gas Dynamic Flowfield and b) Stagnation Bubble Flowfield.

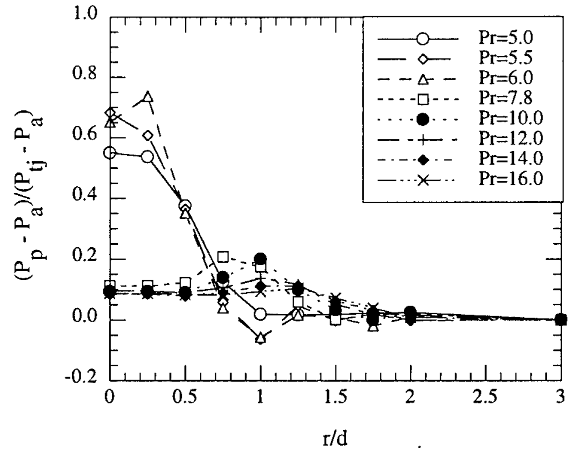


Figure 3. Radial Variation of Impingement Surface Pressure for Various Jet Pressure Ratios From a Supersonic Nozzle.

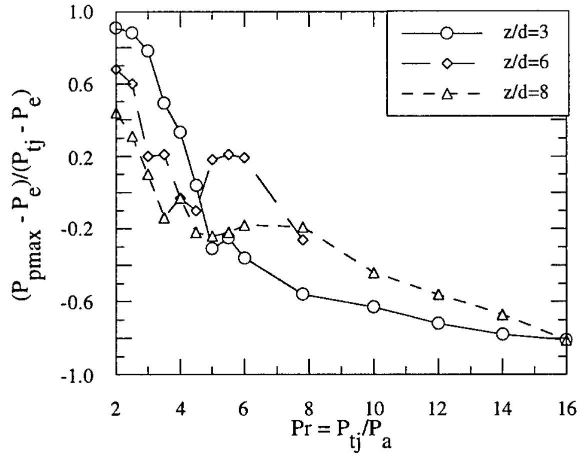


Figure 6. Recovery of Jet Dynamic Pressure at Impact Plate as a Function of Pressure Ratio and Impingement Distance.

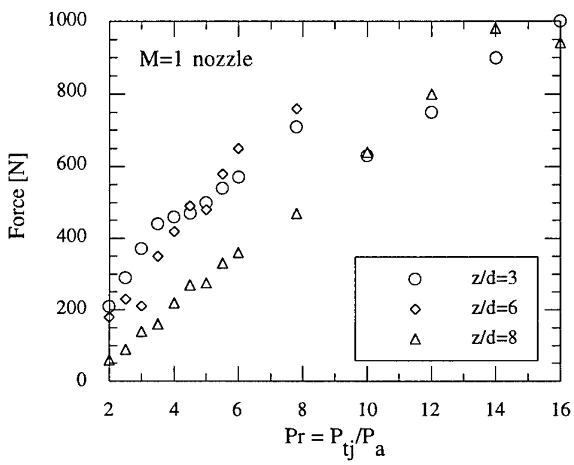


Figure 4. Integrated Force on Impact Plate From Sonic Nozzle as a Function of Distance.

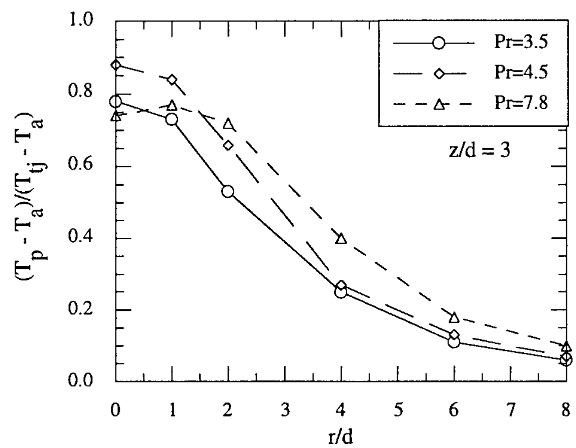


Figure 7. Radial Variation of Dimensionless Surface Temperature for Different Jet Pressure Ratios at z/d = 3.

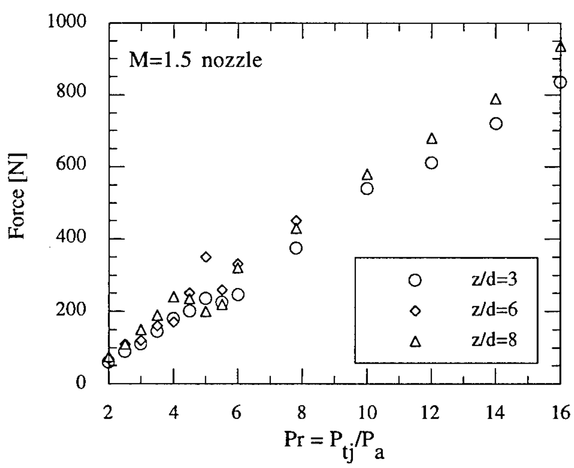


Figure 5. Integrated Force on Impact Plate From Supersonic Nozzle as a Function of Distance.

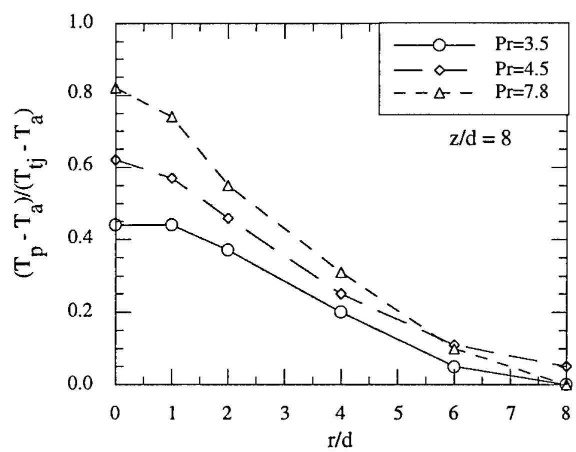
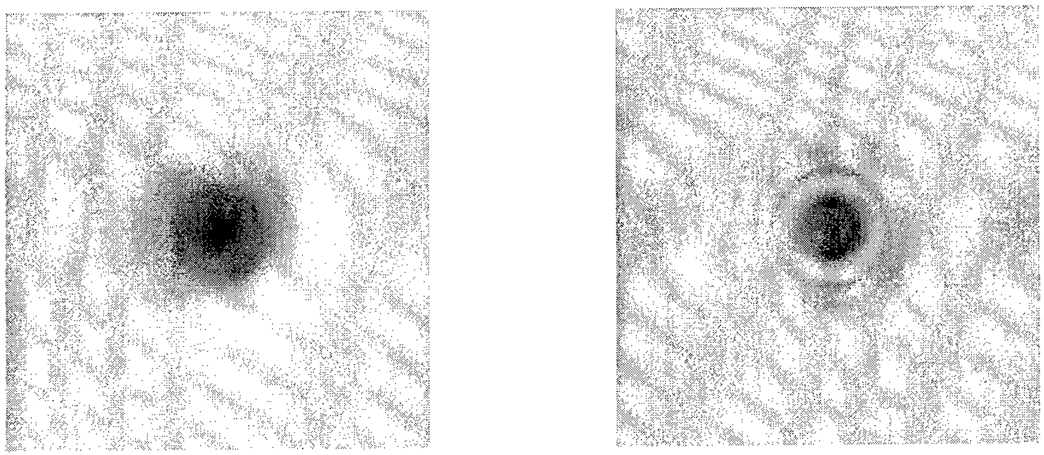


Figure 8. Radial Variation of Dimensionless Surface Temperature for Different Jet Pressure Ratios at z/d = 8.



a) b)

Figure 9. Jet Impingement Surface Temperature Images Using Temperature Sensitive Fluorescent Paint. Dark Regions Indicate Higher Temperatures Than Light Regions; a) Pr = 4.5 With a Stagnation Point Flow and b) Pr = 6.0 With a Stagnation Bubble Flow, Both For z/d = 4.

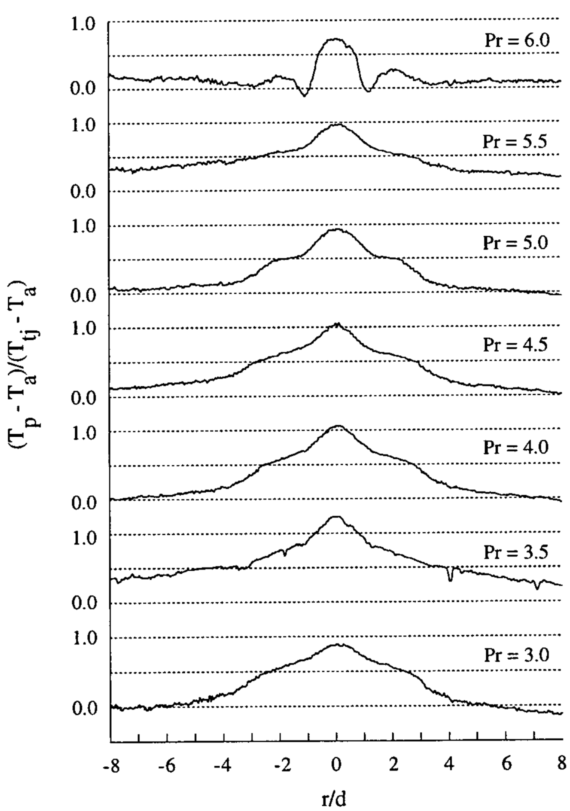


Figure 10. Radial Variation of Dimensionless Surface Temperatures for Different Jet Pressure Ratios Taken From Temperature Sensitive Fluorescent Paint. Mach = 1.5 Nozzle and z/d = 8.

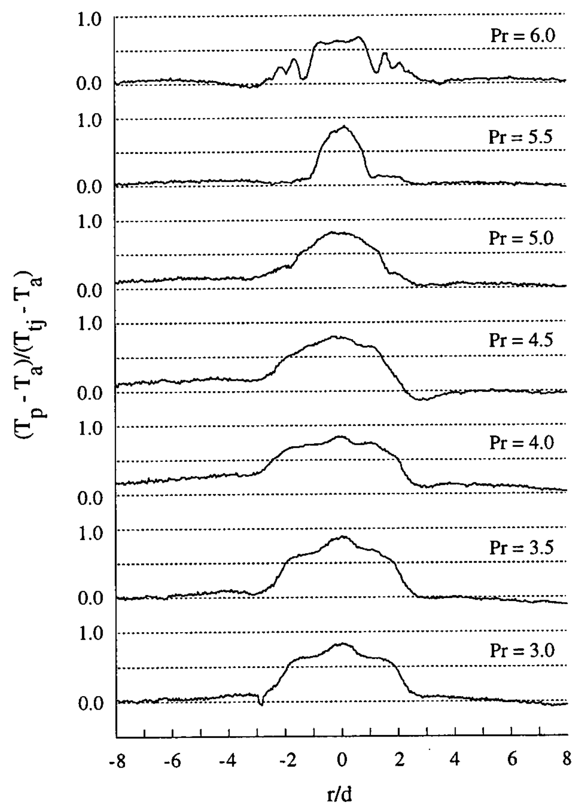


Figure 11. Radial Variation of Dimensionless Surface Temperatures for Different Jet Pressure Ratios Taken From Temperature Sensitive Fluorescent Paint. Mach = 1.5 Nozzle and z/d = 4.

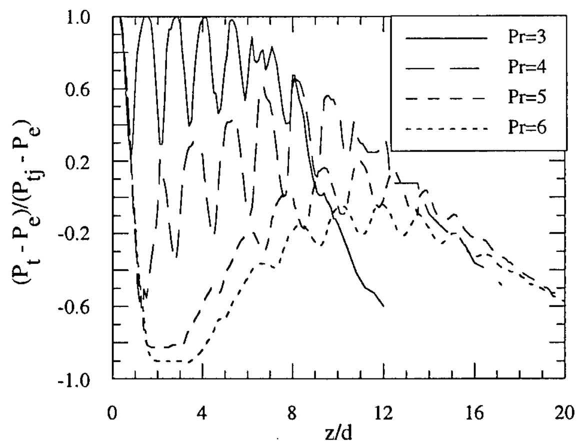


Figure 12. Free Jet Centerline Stagnation Pressure Profiles of Various Nozzle Pressure Ratios.

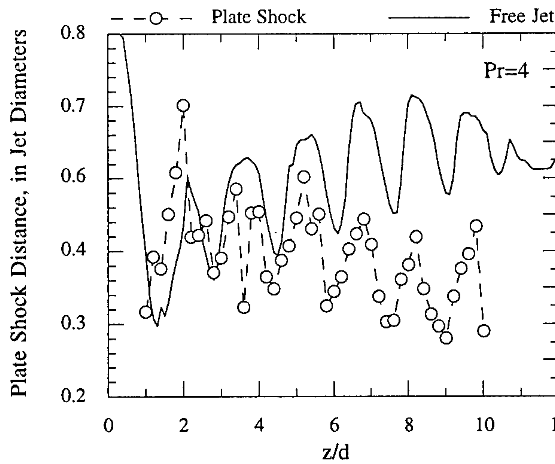
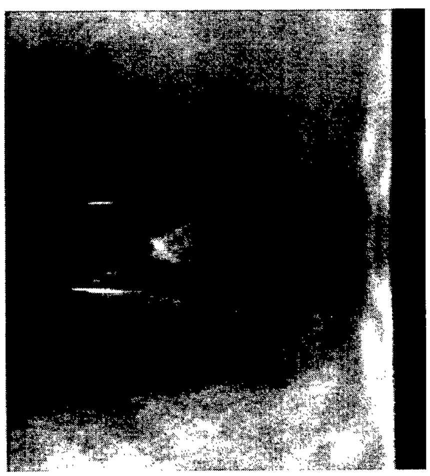
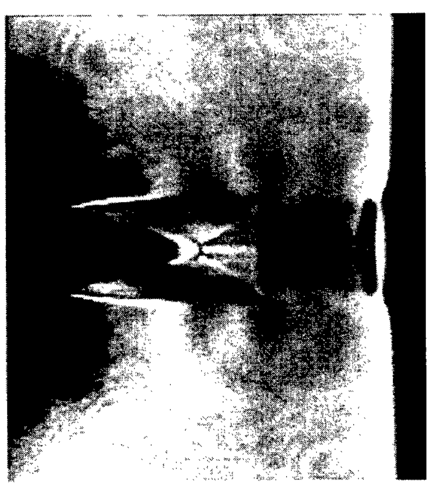


Figure 14. Plate Shock Distance Above Impact Plate to the as a Function of Plate Distance to Nozzle, Pr = 4.



a)



b)

Figure 13. Schlieren Images of Jet Structure in Impingement Region; a) Pr = 4.5 and b) Pr = 6.0, Both For z/d = 4. Conditions are the Same as for Figure 9a) and b).

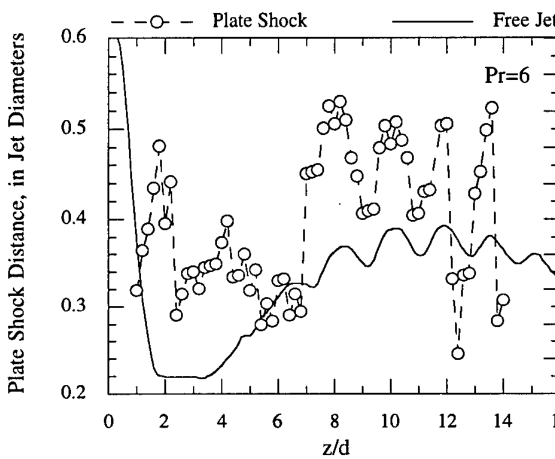


Figure 15. Plate Shock Distance Above Impact Plate to the as a Function of Plate Distance to Nozzle, Pr = 6.

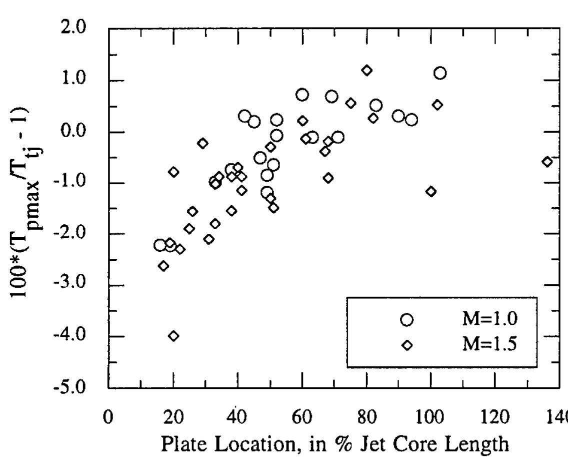


Figure 16. Peak Plate Temperatures as a Function of Plate Location with the Jet Potential Core.

DISCUSSION - PAPER NO. 22

W.B. de Wolf (Remark)

During an incident in our laboratory, we observed that a supersonic hydrogen jet blowing into a cavity can produce local temperatures that may lead to fire. This may have connection to your observation of a plate stagnation point temperature higher than the total temperature of the jet.

N. Messersmith - Author/Speaker (Response)

Thank you for the insight. We wish to add that stagnation point temperatures on an impact plate which exceed the jet total temperature have also been observed in subsonic jet impingement (see refs. 7, 21 and 22), so the presence of an oscillating shock to compress and heat the impingement region does not appear to be an absolute necessity for this phenomenon to occur.

O. Etchevers (Question)

Is it possible to calculate the higher peak temperature observed during the tests than the jet stagnation temperature?

N. Messersmith - Author/Speaker (Response)

Numerical prediction of the jet impingement flow field is quite challenging, since the flow is unsteady, three-dimensional, compressible and turbulent. In the Paper, we devote a paragraph (pp. 22-23) to highlight some of the recent computational efforts in this area (see Refs. 17-20). With the exception of Hong and Jeon (Ref. 20), all the solutions are inviscid. If the surface temperature or heat transfer is desired, though, viscous solutions are essential. Since none of the available simulations were at conditions that would be expected to produce such a high stagnation point surface temperature as seen in our experiments, it is not known at present whether any of these solutions would predict these high surface temperatures.

"STRUCTURAL DESIGN CONSIDERATIONS FOR AIRCRAFT FIRE SAFETY"

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0. Summary

Fire cannot be completly prevented by design and material means, in particular those caused by armor piercing munitions.
Structural aims are therefore

- to keep the fire within the fire zones, which are designed to withstand fire exposure for a certain time accepting strength degradation.

- to protect the primary structure, essential for structural integrity.
  Protection can be provided by
  - Separation
  - Sealing
  - Insulation
  - Ventilation (cooling)

- to select heat resistant materials in these areas accepting mass penalties.

- to provide redundant load paths, accepting reduced strength capability.

- to size critical structural elements for limited fire/heat exposure.

In case of fire non-destructive and destructive methods to determine the residual strength have limited reliability due to the unknown temperature and time the structure has been exposed to. Temperature-gauge-plates in the fire zones could ease the problem.

1.0 Introduction

With the replacement of conventional metallic materials and the introduction of advanced composites for primary and secondary aircraft structures additional design considerations for aircraft fire safety are required, both in general configuration layout and detail component design.
Lightning strike- and EMC- threats for the A/C-structure, the protective measures to prevent fire or to survive fire are discussed and the result on pilot and ground crew health are presented.
Design features to ensure structural integrity during engine compartment fire are shown for a typical fighter A/C configuration.
The affects of fire on material strength and resulting structural integrity are shown, available nondestructive testing methods for heat exposure of composites and residual strength predictions are discussed.

2.0 Physical background / Threat

2.1 - Possible sources for fire development in aircraft structures

During standard operation:
- engine fire,
- lightning strike,
- short circuits,
- gun fire,
- leakage of hot gas pipes and fuel pipes or tanks.

Aircraft battle damage:
fuel leakage, hot gas leakage, introduction of fire sustaining components, sparks damage of heat barriers.

During ground operations:
- refuelling/ defuelling

Mishaps during take-off or landing and crashes.

2.2 - Fire development by lightening strike: Inherent risk of tank compartments and fuel pipes

The correct aircraft design according to FAR regulations shall exclude fire development by lightening strikes. The design must therefore guarantee that the following conditions will be avoided:
- Local thermal heat-up of structures to about 200°C or higher.
- Generation of sparks (e.g. between parts with insufficient electrical contact).
- Ohmic overheating in case of insufficient electrical cross sections.
- Misdesign of muliple earthings points could result in local induction-caused sparks.

2.3 - Requirements, Specifications, Standards

The major requirements, specifications and standards

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

with respect to structures are listed below.
MIL-F-87154: Hazard and failure concept
MIL-F-38363: A/C-Fuel system; Fire hazard reduction; Explosion suppression
FAR 23/25: Civil airworthiness standards

2.4 - Definitions

A material is called "*fire proof*" according to FAR when it passes a burner test with a flame temperature of 1093°C ± 28°C for 15 minutes. Fire proof materials are requested e.g. for fire walls.
To be classified as "*fire resistant*" a material has to widstand this burner test for 5 minutes.
"*Self-estinguishing*" materials must pass a vertical self-extinguishing test (FAR23, Appendix F), were the average burn length does not exceed 6 inches and the the average flame time after removal of the flame source may not exceed 15 seconds. Drippings from the material may not continue to flame for more than an average of 3 seconds after falling.

2.5 - Fire detection

For more than 40 years special sensors are used on board of civil and military aircraft to detect overheating or fire. Best known and developed to a high degree of reliability are the engine bay fire detectors. They are to be found in every engine bay of civil and military aircraft. These detectors are designed either as a continuous sensor tailored to the geometry of the engine bay (fire wire) or as a spot sensor installed close to a possible fire source on the engine. The signal created by a conductivity or pressure change in the sensor or by means of a bi-metallic device, gives a warning to the pilot and/or releases the on-board fire suppression system.

For fuel tanks and equipment installation bays especially of military aircraft optical detectors in the UV- or IR-wave length range have been developed. These detectors are able to sense the very fast hydro-carbon fires within milliseconds and trigger the extinguishing - system before a dangerous pressure level in fuel cells or dry bays has been reached. A combination of both sensor types minimizes the possibility of false alarms.

2.6 - Effect on structures

Reduced residual strength due to
- thermal exposure beyond the irreversible threshold,
- burned off matrix-material.

3.0 **General structural requirements**

One major goal is to improve the survivability and to provide structural integrity in case of an inflight fire. Methods to meet the a.m. requirements are:

3.1 - General configuration layout

Fire shall not cause critical structural failure or prevent recovery of the aircraft.
The inboard profile of an aircraft configuration must provide adequate separation of fire zones from areas necessary for safe flight i.e. cockpit, fuel tanks, power supply, critical structure.
Separation of fuel tanks is one of the most efficient methods to reduce the threat cause by armor piercing.

3.2 - Materials - burning conditions

The standard metallic structural materials (Mg-, Al-, Ti-alloys and steels) are not flammable in the case of static volumic components even during small and more extended fires. Only in cases of large fires of longer duration materials such as Magnesium- and Titanium-Alloys start to burn at temperatures close to the melting point or in the molten state. The conditions of titanium engine fire are very special and are treated in Paper 25.

3.3 - Structural Analysis and Damage Tolerance

The selection of structural concepts and materials for aircraft design is still driven by the three major structural design criteria

* Lightweight
* Stiffness
* Strength and Durability

influencing the development not only of new advanced materials both in the metallic and nonmetallic area, but also in the field of design principals and detailed structural analysis.

With these requirements and dedicated loadpathes within the structure, attention must be payed to local load-introductions as well as superposition of loads and environmental effects incl. thermal loads, influencing the performance of the material.
The result is very often either thin-walled stiffened skins and/or sandwich structures to ensure the structural integrity with respect to loads and functional requirements by using material properties to a max. degree.
Fig.3.3-1 shows the percentage of different material properties, based on the structural A/C-weight, which are critical for optimum component design of fighter aircraft.
To combine the three major criteria, material modulus and ultimate strength, divided by the density (specific strength and stiffness) indicate advantages of modern fibre reinforced composites of 40 - 80 % depending on the type of fibre. Together with additional benefits in the area of fatigue and advance these materials here been introduced into structural elements of modern military and civil A/C, with improved mechanical properties for each generation of fibre and matrix materials.

Thermal loads in structural analysis act usually in combination with mechanical loads, for supersonic A/C these are mainly generated through aerodynamic heat-up, creating temperatures between 100°C and 120°C (212F and 248F) in skin and substructure, while subsonic aircraft are limited to 70°C to 85°C (160F and 185F), mainly due to sun exposure and

heat radiation.
The second major source of heat, influencing the structural design is the engine bay and reheat section of the engine, generally the aft fuselage. In some areas also system temperatures are a main factor of thermal design criteria, i.e. heat radiation from tire/brake systems in landing gear wells, hydraulic fluid cooling systems etc ..

Analysis and damage tolerance requirements for structures are defined in accordance with the A/C-mission-and performance-specification. Analysis criteria are developed from these requirements and used during the stress layout process of structures. The most important goals of this analysis are:

* meet stiffness requirements,
* check for static ultimate strength,
* check for fatigue strength and fulfill the "life requirement": safe life / damage tolerant,
* ensure function of systems.

Therefore most parts of an A/C structure are designed to withstand the mechanical loads in combination with the max. **design service temperature**, defined by either aerodynamic heat-up and/or system temperatures.

For composite materials the superposition of mechanical loads and temperatures is related to the reduction of matrix based properties of the epoxy material, i.e. compression and shear strength at elevated temperatures and after moisture pick-up from the environment.
The links between these environmental conditions and the mechanical behavior of the resin material dominates the selection of a composite material for a given A/C-configuration and is part of the material qualification process and the generation of "material allowables", used by the stress engineer during structural analysis.
Possible damage szenarios and damage tolerant requirements for composites focus almost exclusively on mechanical damage, Fig. 3.3-2. The lightning strike damage is the only combination of mechanical damage and local heat-damage to be considered.
The mechanical energies, applied to the structure in a "Low velocity impact"-szenario are comparatively small (8-30 J) resulting in delaminations between individual plies and at the edges of components and influencing the stability of the damaged region especially when compression loads are applied.
Therefore todays primary aircraft composite structures are designed not to exceed a strain of approx. 50% of the material failure strain at ultimate load conditions.

This limit ensures that a certain amount of damage can be tolerated without compromising structural integrity and safety of flight and the repairability of structures, damaged beyond these limits.
If structures are damaged, the two most important questions to be answered are:

1. What is the immediate impact of the damage to the strength and function of the component ?
2. What is the probability of the damage to grow beyond safe limits during continiung service and if so, what is the growth rate ?

To answer these questions, the first and most important step in the whole process is *"Damage Evaluation"*, since all future actions will base on the results of this task.

3.4 - Damage Evaluation (NDI=Non Destructive Inspection)

Composite
With the introduction of advanced composites in load-carrying A/C- structures new NDI techniques became common standard for aircraft inspection. While metal aircraft structures were primarily inspected for cracks and corrosion, for composites with their sensitivity to disbonds and delaminations the following techniques were adopted:

* during component production:
  - Ultrasonic squirter technique (US-C-scan)
  - X- Ray
  - Manual "Tab-checks"
* during aircraft service /maintenance:
  - Ultrasonic technique (US-A-scan)
  - Tab-checks.

For the detion of chemical or heat damage non of the above methods provide results, that can be transfered into data, usable for assessing the effects of the damage or even more important, provide information about the reduced mechanical properties of the damaged part.
The methods used at DASA previously for heat damage assessment of composites are:

* Thermogravimetric Analysis(TGA)
* Infrared Spectroscopy.

Both methods require extracted samples of damaged material from the aircraft and are performed in the laboratory.

"On Aircraft" methods are limited to inspection methods adopted from metal structures i.e. Surface Hardness Test (Barcol hardness), taken on the exposed side of the laminate, results are limited to cases of short exposure times and temperatures less than 500°C (940F). Correlation to strength properties must be obtained via artificial damage of test-coupons.

Metals
In general, if to evaluate a possible degradation in strength caused by fire overheat with NDI methods like (micro)hardness testing (and)/or electrical conductivity measurements are used. Thereby it is a common problem, that time and temperature of heat exposure is not precisely known.
The first impression of fire or overheat damage can be derived from an evaluation of a possible *discoloration* of primer or topcoat. This must be done after careful removal of soot or smoke products and

yields to a first order estimation of local extent and temperature and time of exposure. The next deeper assessment is done by the *measure of hardness and electrical condutivity*. It must be noted, that the different types of structural materials behave different:

- *Aluminium alloys* usually show an increase in electrical condutivity with increasing exposure temperature and time. The level itself and its increase is individual to different alloys and tempers, but it is a very sensitve parameter for the degree of heat exposure or overheat. However the correlation between conductivity and residual room temperature strength becomes very inaccurate after exposure to temperatures close to typical heat treatment temperatures for the respective alloy. The strength information derived hereof is more or less qualitative: not effected, minor reduction, strong or very strong reduction. The hardness (microhardness) however decreases with increasing heat exposure but it is even more ambiguous to evaluate. Alloys can endure temperatures between 120°C and 180°C without significant inreversible degradation depending on the alloy, its temper, the exposure time and amount of property change allowed.
- The measurement of electrical conductivity however gives no indication for a possible fire or overheat damage of *titanium alloys*. Also hardness remains unchanged up to the temperatures where oxidation of the alloy dominates. Then an increase in microhardness becomes visible, because the formed oxygen enriched "alpha-case"-layer is harder than the base metal. This occures only at temperatures at 500°C or above, a temperature level where aluminium structure parts start to melt. Up to this temperature level, titanium and its standard alloys are practically not sensitive to degradation. Exceptions must be made where parts are plated with cadmium.
- *For steels*, the hardness at room temperature drops with increasing heat exposure. In general, there exists a good correlation between hardness and strength, which allows an indication whether the alloy was effected and a rough estimate on a possible degree of degradation. But for detailed stress analysis this correlation must be verfied for each individual alloy. Conductivity measurements do not give meaningful results for steels. Many stainless steels are not significantly effected by temperatures up to 450 or 500°C. But alloyed steels and maraging steels can start to change their properties even at temperatures below 200°C.

Discussion on the potential and limits of an NDI assessment:

NDI testing of hardness and conductivity can be performed by qualified personnel on aircraft, wherever access is possible. Precise hardness measurements require better accessability than conductivity investigations and special care has to be taken during hardness measurements on thin walled areas.

The great advantage of these two tests is their easy and quick accomplishment and the high spatial resolution allowing distinction to be made between undegraded and degraded zones and allowing a local mapping of the degree of fire or overheat damage. Beyond this mapping, however a lack of data prevents establish ment of a strict correlation between measured properties and strength degradation. To overcome this at least for non fatique critical components, methods are:

- A conservative repair, with the definition of an uneffected zone and an area with minimum strength.
- A subsequent localized destructive investigation programme using small tensile specimens from the maximum degrated zone and possibly some intermediate zones with subsequent stress analysis and repair.
- A small test programme, overaging a set of tensile specimens in the estimated time/temperature range and to determine hardness and/or conductivity. The correlation between the results and the measured data from the component will supply data for a stress analysis and repair.

In addition, the assessment and repair of damage caused by fire or overheat must distinguish between aircraft battle damage repair and standard repair allowing the full aircraft operational capability.

Degradation material in strength can be determined up to a certain limit by this NDI methodes, another problem, caused by fire on long term: Corrosion, which might be promoted be the release and transfer of acid containing smoke.

3.5 - Design rules / guidance

The design aim is to ensure that aircraft structures/materials are not exposed to temperatures by fire or overheat above those listed below.

Material	Short term exposure without loading	Short term exposure with applied load
Al - alloys T7X - temper	≈ 175°C	reversible strength reduction acc. MILHDBK 5G
CFC - epoxy-systems - BMI-system	≈ 200°C ≈ 250°C	≈ 130°C ≈ 200°C
Sealant - Polysulfide - Fluorsilicone	 ≈ 200°C ≈ 250°C	---

Not only structural materials but also nonstructural materials i.e. sealants, surface protections are to be considered. Generally the following possibilties are used to lower thermal loading on the primary structure.

Sealing: Fire zones are to be sealed providing two independent liquid- and / or vapor-proof barriers.
Insulation: Elements / components essential for stuctural integrity are to be insulated by blankets (steel or ceramics) to keep the temperature resulting from fire or radiation below their individual limits.
Heat transfer from a heat source (fire or other hot spots) to not directly exposed structure has to be checked carefully.
Ventilation: Both insulation as well as heat transfer reduction can be supported by ventilated space between structure and the nonstructural barrier. Ventilation also reduces the risk of unsafe conditions due to critical air-fuel vapors.

To reduce the risk of fire caused by fuel ingestion into the air inlet duct, common walls are to be sealed carefully and redundantly.

4.0 Requirements for Composite Structures

4.1 - Strength Property Degradation due to Excessive Temperatures

In general, temperature exposure above the established service temperature of a thermoset material must be considered as damage inducing, however short time exposure to higher temperatures has been endured without significant strength reduction. For Carbon Fibre Composites (CFC), the physical damage is limited to the matrix, in most cases a modified epoxy material. Factors which can greatly influence the amount of damage are laminate thickness, the amount of moisture in the laminate and the heat-up rate.

For epoxy resins, cured at 175°C the experience is as follows:

* Exposures to 400°C and higher will cause damage within seconds
* Exposures to 250°C can be tolerated for some minutes
* Exposures to 200°C can be tolerated for approx. one hour.

Damage is found in the form of resin cracks, delamination of plies and blistering to total decomposition of the matrix material.
Since the matrix is primarily used for fibre stabilization (compressive loads) and shear transfer through the laminate layers, the respective engineering properties are affected; additionally properties like bearing strength around fasteners are also reduced.
Tests with 20 ply lamiantes, damaged by 400°C over 1.5 min. have shown compression strength reductions of approx. 30 % at room temperature.
Due to the strong orthotropic behavior of the individual plies the damage of a laminate depends also on the "through the thickness damage rate" and the stacking sequence of individual ply-directions, whereas for isotropic materials like metals the through the thickness effects can be neglected.
Longterm effects on chemical stability and repeated mechanical/environmental loads of heat damaged composites are yet to be assessed.

4.2 - Concepts for retardation and/or avoidance of flammability by materials selection.

A standard practice for the protection of composite materials from fire or overheating is the application of fire retardant coatings with a thickness of less than 1mm. Exposed to temperatures of about 300°C these coatings (intumescent paint) start to decompose. For some special applications, several plies of a glass fibre reinforced silicon matrix product (i.e. 900Si2/400) are applied to a composite part. This serves fire proofing and/or self-extinguishing requirements and in addition, the glass fibres can carry load. This dual function of the material can produce lightweight structures.

4.3 - Toxicity of combustion products.

Faced with an open aircraft fire, it is very important to

realize that it is impossible to predict all or at least most toxic and intoxic products from nonmetallic materials generated and released by the fire. The situation is complex, because of uncontrolled mixtures of different nonmetallics, unknown local temperatures and unknown oxygen content. Toxicity and formation of combustion products is presently under intensive investigation.

Nonmetallic materials are present in modern aircrafts as:

- fibres for composites: carbon and glass,
- composite matrix: epoxi, modified epoxi, BMI,
- honeycomb cores (e.g. Nomex),
- sealants,
- fillers, potting components and shim material,
- primers and paint.

Combustion products with high toxicity which can or will be released from such nonmetallics under certain circumstances are:

- carbon monoxyde,
- nitrogen oxydes,
- hydrogen chloride,
- carbonylchloride (phosgene),
- hydrogen fluoride,
- sulfur dioxyde,
- cyanic products like hydrocyanic acid,
- dioxine and furane,
- strontium or zink chromates,
- antimony trioxyde,
- asbestos (from elder aircrafts).

Most of such toxic products are volatile and are no longer present in hazardous concentrations a short time after the fire extinguished. However there are some products remaining which could cause health hazards during repair and maintenance work.

5.0 **Preventive measures**

5.1 - Actual Trends in Materials Selection

Driven by legal and environmental restrictions for production and application of hazardous products, strong attempts to reduce or partially to avoid toxicity hazards have been undertaken in recent years in materials research and in the philosophy of materials selction. A very early example is the ban of asbestos formerly used in nonmetallic products such as sealants for high temperature applications. The use of cadmium coating has been reduced in stages by replacing alloyed steels with stainless steels wherever possible. Consequentely, the structure of the Eurofighter is already free of cadmium. Chromate free primers have been developed and investigated for aerospace application to replace conventional chromate containing products. Today they are introduced into serial batch production. To reduce toxicity hazards from electric and electronic equipment, broad investigation and development programmes started in recent years. The aim is to reduce or eliminate halogenic and other toxic flame retardants without reducing the required mechanical and electrical properties.
The stepwise realisation of these environmental improvements reduces toxicity hazards significantly. But, presently there is no way visible, to avoid toxicity in smoke and char and pyrolysed products completely.

5.2 - Structural Redundancy and Multiple Loadpathes

The concept of structural redundancy has been applied to aircraft structures for important loadpathes and load-introductions between components like wing to fuselage interfaces or fin/rudder attachments mainly for safety reasons. In principal the concept requires the capability of a structure to allow safe operation of the aircraft up to a defined load level with one primary structural element completely failed. The remaining elements are therefore designed for these "failure cases" to withstand the new load-distribution in the structure and the locally higher loads for a limited time of operation.
Beside "classic" interface structures the design of components like wings or fuselage structures feature redundant loadpathes through their "multiple element" design, where parts like shearwalls, spars, ribs etc. are already multiple present for stiffness/functional requirements of the overall structure. This multi-element design principle is analysed for the case of failure of one principal element and recovery of the aircraft with reduced maneuver loads ("fly home"-principal), enhancing the capability of the structure to withstand severe fire damage in a confined structural region. Fig. 5.2-1 shows one example of a fuselage section and an alternative load transfer of the wing lift (Q) to fuselage elements within this section.
The right half section shows primary shear load transfer from the wing section (I) through the wing root (Q_1) into the wing carry-through bulkhead (II) where the sideskin (Q_2) and the longitudinal shearwalls (Q_3) are attached, balancing inertia loads from the fuselage mass.
The left half section indicates a failed (or destroyed) sideskin between two bulkheads with the bulkhead now dumping the shear load two a larger degree into the shearwalls (Q_3') and also the engine ducts (Q_2'). In case of more extensive damage (i.e. bulkhead and/or outer duct skin) this section in total would pick up less wing lift and the remaining two interface points would act as redundant structure, carrying additional loads. Similar redundancy is available for other loads like wing bending moments.

5.3 - Measures against lightening strike for CFC and GRP-Structures.

CFC structures with volume fractions of up to 60% carbon fibres have insufficient electrical conductivity to ensure effective lightning strike protection. Therefore, additional efforts have to be made:
A proven standard is to apply a fine copper mesh as an outer composite layer. An effective electrical joining between composite parts or between composite

parts and metallic structure parts is achieved in most cases by special metallic fasteners such as bolts and rivets. For some applications additional flexible bonding leads can be required. Access doors and rows of rivets especially in tank areas, however, are protected with an additional upper layer of aluminium foil or mesh.

The protection of GRP designed is in the same way as for CFC.

Composite parts with special electrical requirements like radomes are commonly made from GRP, a nonconductive material. However, some lightning protection is required which is commonly provided by continuous metallic button strips electrically bonded to the metallic airframe structure by flexible bonding leads.

5.4 - Measures to prevent fire extension

Aircraft are generally designed in such a way that possible fire zones such as engine bays etc. are separated from the remainder of the aircraft. Furthermore, hot spots and/or equipment installation bays which could promote a fire or support the spread of fire from one zone to the other become isolated from each other by special design.

Engine bay fire walls of military aircraft are designed by material selection and/or insulation to withstand a fire of 1100° C for 5 minutes. Metallic or foam type fire traps are used to prevent the spread of a existing fire into an adjacent bay. Careful selection of fire retardent or self-extinguishing materials helps also to keep fire under control inside a separated and/or protected bay. Overboard dumping of leaking fuel and fire suppression equipment installed in bays with ignition sources are further measures to prevent fire extension.

Inside fuel tanks a complete or partial installation of special foams with open pores is a well-known technique to prevent fuel ignition and flame progression.

5.5 - Fire Extinguishing Techniques

The task of an active fire suppression system is - if once released - to distribute the limited amount of extinguishing agent on-board (normally a one-shot system) within the shortest time and in a sufficient concentration into the burning bay (see Fig. 5.5-1).

Fluid gases like Halon and suppression powders are used on board of civil and military aircraft. Halons are now banned by the Protocol of Montreal; the search after a substitute agent is in progress. Powders like $NaHCO_3$, $KHCO_3$, $K2SO_4$, KCL, $NH_4H_2PO_4$ or $(NH_4)\,_2SO_4$ are also very effective but they need scheduled maintainance and proper cleaning of an aircraft and its equipment after discharge.

Gases and powders are stored in bottles of different shapes and sizes. Some types become pressurized during the filling process and release the suppressant over a fast reacting valve. Others use pyrotechnical devices for pressiurization, bursting of the agent container and distribution into the fire zone. The fire is suppressed by a chemical reaction of the agent under influence of the heat.

5.6 - Precautions during repair and maintainance work:

The handling of parts from a crash site, or of parts exposed to fire or overheat requires precautions to be taken. Such protective measures are breathing apparatus, gloves and eye protection. This holds true also for mechanical rework of composite parts i.e. drilling, cutting and machining, where the matrix burns rather than the carbon fibres. Carbon fibres of a burned matrix are then unprotected and can undergo a reduction in diameter. During rework of such composite parts the above mentioned protective measures are sufficient. The extended use of nonstructural materials in the equipment (i.e. cable insulations, electric and electronic components, fluids) contributes to toxicity of combustion products. Fragments of nonmetalic materials but also metalic components in terms of adherent products can carry toxic risks:

- cadmium from plated parts in terms of evaporated and condensed dust, resolidified particles and the cadmium plating process itself.
- adherant chromate particles from primers,
- partly charred or pyrolysed organics, e.g. fluorine-chlorineated rubber products,
- adherent toxic smoke products,
- released asbestos.

6.0 **Examples**

6.1 - Engine bay

Typical fire protection of the primary structure features:

- fire proof titanum tunnel-skin to protect elements of primary structure such as fin attachment bulkheads
- fire proof blanket (sandwich) to protect the engine face frame (wing attachment and rear end of integral fuel tank).

See Fig. 6.1-1

6.4 - X-31 Fire damage after crash

The X-31A, an experimental aircraft with CFRP wings, experienced ground impact after pilot ejection with the left wing completly destroyed by impact and subsequent fire and the right wing largely intact but severly damaged by fire on the lower surface. Since the fire extended from the fuel cells in the fuselage (dry wing) to the wing tip, damage decreased in spanwise direction. Fig. 6.2-1 shows the various stages of heat damage to the carbon fibre skin laminate, from total disintegration of the laminate at the inboard edge with only the carbon fibres remaining (I) to light paint blistering and colour changes at the outboard tip (II).

- Material stiffness 47 %
  - skin buckling
  - control efficiency
  - allow. deformation
- Notched material strength 37%
  - skins and substructure
  - longerons
- Bearing strength 11%
  - load introductions
- Damage Tolerance/Repair 5%
  - allow. impact energy
  - residual compress. strength
  - repair patch

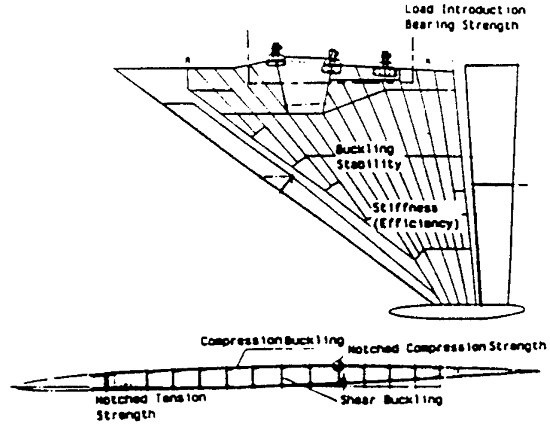


Fig. 3.3-1 Structural selection criterial for aircraft materials

- Component manufacturing and Assy:

- Lay-up errors
- Mylars
- Cure cycle
- Fasteners
- Handling

- Inservice:

- A/C-Usage / Overhaul
  - Erosion
  - Impact
  - Heat
  - Overloads
  - Ballistics
  - Lightning
  - Media

- Delamination
- Porosity
- Edge delams /cuts
- Missdrills
- Scratches / Ply separation
- Penetration / Ballistics

Fig. 3.3-2 Damage Szenarios for Composite Materials

Section through center fuselage at wing carry-through bulkhead

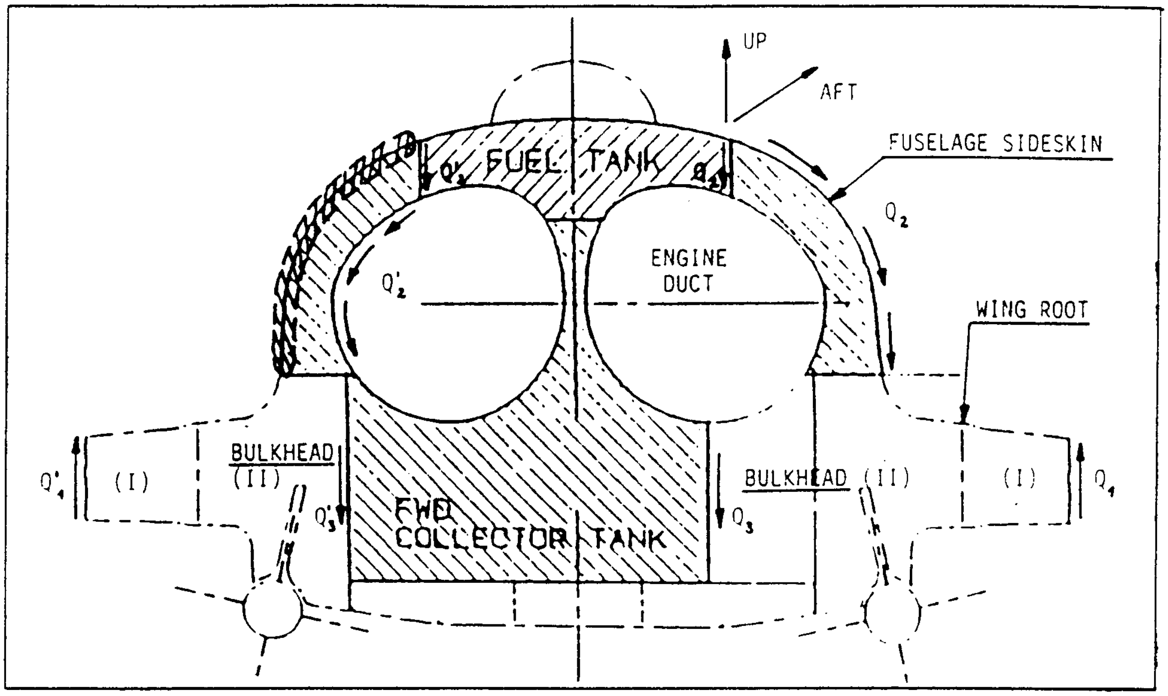
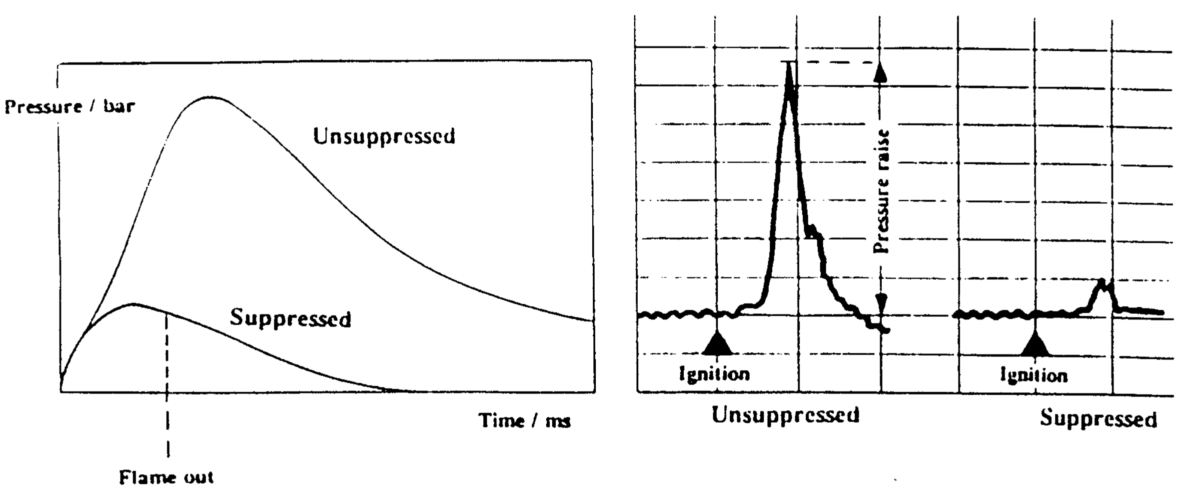


Fig. 5.2-1 Structural Redundancy in Fuselage Components



Pressure Raise of a Suppressed / Unsuppressed Hydro-Carbon Fire

Fig. 5.5-1 Fire Extinguishing Techniques

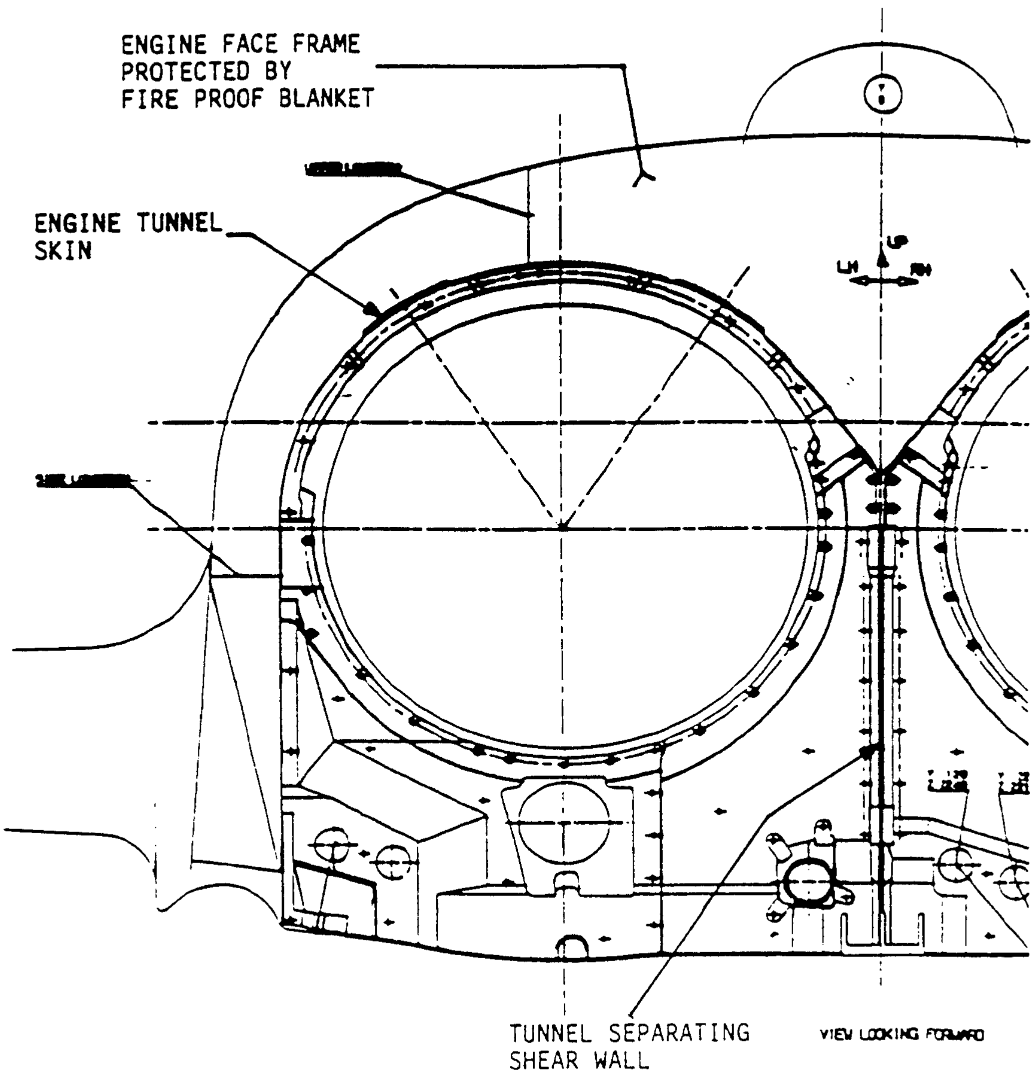


Fig. 6.1-1 Typical engine bay section

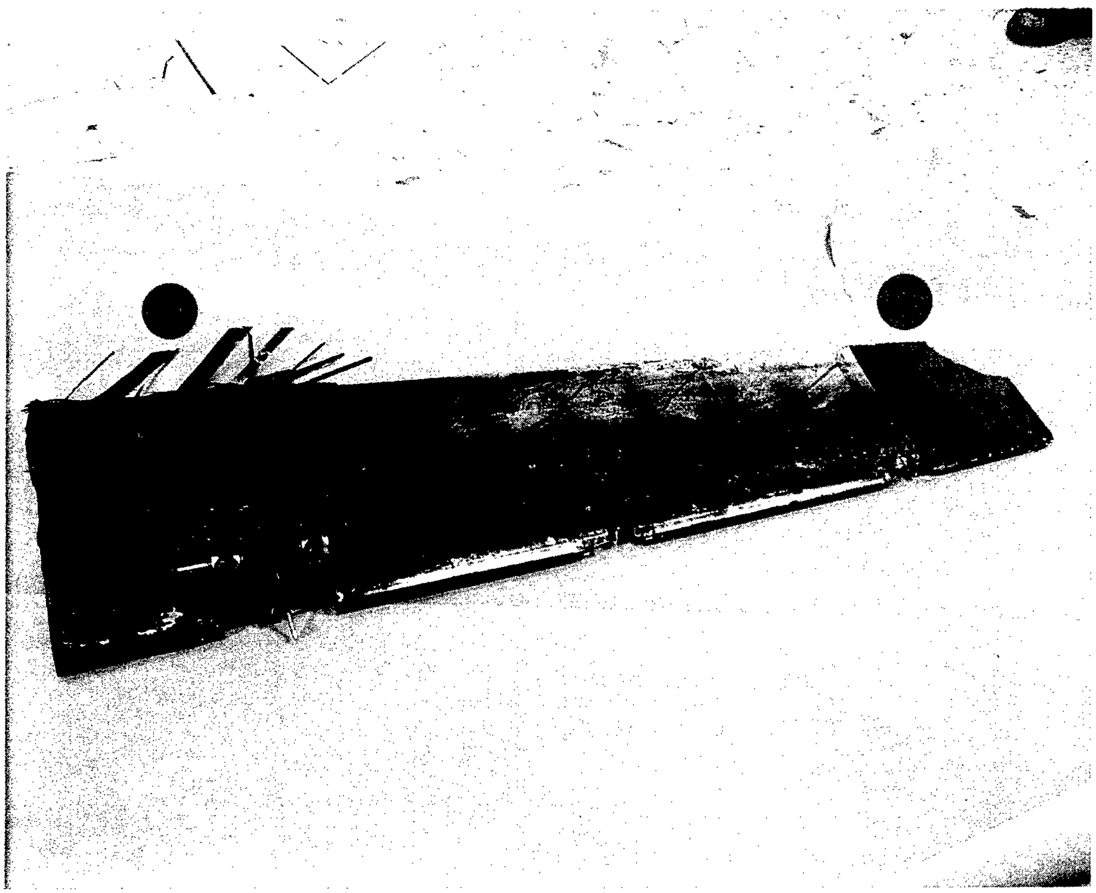


Fig. 6.2-1 X-31 - Flap: Composite structure damaged by fire

DISCUSSION - PAPER NO. 23

J. Andrews (Question)

1) You say that you avoid hazardous materials during selection. Many materials become toxic when they burn. How do you consider this?

2) The composite flap fire damage - Did you experience a release of fibres and how did you protect against it?

M. Voglsinger - Author/Speaker (Response)

1) The above-mentioned statement refers to structural materials for future programs only.

Composites: The metallic structural materials which we selected are not considered to be toxic in the temperature range below 1100°C (test temperature). Protective treatments are also free of cadmium, chrome, lead and zink.

General: Composite materials such as GRP and CPC are usually considered to be fireproof. Toxicity of composite matrix materials cannot be precisely predicted due to their unknown parameters of combustion conditions. This is also valid for sealants and coatings. Toxicity of such combustion products is under investigation. There is no evidence that fibres become hazardous after the exposure.

2) We did not experience release of fibres; nevertheless we recommended protective measures such as gloves and eye protection .

R.G.W. Cherry (Question)

In JAA (civil) certifications, structural factors may be determined for system failure conditions such that the more probable failures affecting the aircraft structure result in higher factors, and less probable failures in lower factors. The relationship between probability of occurrence and factors is prescribed as part of the advisory material to the certification basis. What is your opinion on a philosophy of this kind being adapted for the strength of aircraft structure following degradation by fire or structural damage as a result of explosions?

M. Voglsinger - Author/Speaker (Response)

1) Structural factors for strength analysis of A/C components today are primarily "safety factors" used on external loads data (Limit Load Concept) to prevent structural failure, i.e. j=1.5; or factors implemented to account for material/process variations, i.e. 1.25 for castings.

2) The structural analysis process with respect to strength and rigidity of airframes is strictly deterministic; however, first, probabilistic approaches are discussed for advanced "active controlled A/C" with partially "care-free handling" manoeuvre performances.

3) Safety factors as above have been modified for these aircraft i.a.w. certification requirements, but the process of analysis itself is still deterministic.

4) As explained, excessive heat due to on-board fire or explosions and their detrimental effects on the material and therefore component strength are not a "design case" for the structure presented. The system requirements are fulfilled with fire detection, suppression and/or design features like fire walls and structural redundancy already present in the design.

5) In case in-flight fire damage, survivability should become a certification requirement for civil or military aircraft; most likely this will be treated on a probabilistic approach with respect to the loads that must be endured and the areas of a structure affected, i.e. superposition of the max. lateral gust loads for a vertical tail and the residual strength due to fire damage for a rear-fuselage-engine A/C.

We hope we this answers your question adequately; in case there are further discussions required, don't hesitate to contact us.

BURNTHROUGH RESISTANCE OF FUSELAGE AND CABIN STRUCTURES

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ABSTRACT

This paper describes the joint research project undertaken by the United States Federal Aviation Administration (FAA) and the United Kingdom Civil Aviation Authority (CAA) to evaluate and improve upon the fuselage burnthrough resistance of transport category aircraft to large fuel fire exposure. In an earlier project several surplus transport aircraft were exposed to large area fuel fires. During these tests, the fire entry points, likely fire paths to the cabin, and time frame involved for this to occur were investigated. The current project is an extension of this earlier work

The project is divided into several phases: development of a full scale testing device, development of a medium scale testing device, and follow-on research leading to the potential development of specifications for materials, systems and components which would increase fuselage burnthrough resistance. The CAA tasked Faverdale Technology Centre (FTC) to develop a medium scale test apparatus. FTC completed construction of the testing apparatus in 1993. The FAA had the responsibility of developing a full-scale burnthrough test rig, which was completed in 1995, at the FAA Technical Center in Atlantic City. Several tests have been completed in the full scale test rig. The test results of both the medium and full-scale rigs will be discussed, along with future considerations.

In Europe an Industrial consortium led by Airbus Industrie will be proposing an Industrial Materials and Technology research project to the European Commission. This project will build on the work initiated by the Authorities. The objective is to identify materials and processes capable of substantially improving burnthrough resistance and also capable of being introduced to aircraft production lines in a timely and economical manner.

INTRODUCTION

Post crash fires are usually initiated by the spillage and subsequent ignition of jet fuel released by the fuel tanks damaged as a result of the crash. Because of the potential severe fuel fire hazards in accidents with major spillage, the FAA has supported research programs for anti-misting kerosene and fuel system crashworthiness that aim at minimising or eliminating the fuel fire hazard. Although the size of the fuel fire is certainly important, other factors in the postcrash fire scenario may be of even greater importance. One such important factor is the integrity of the fuselage during an accident. Two possibilities exist: 1) a crash rupture or emergency exit opening exists, allowing direct impingement of flames on the cabin materials by an external fire, or 2) an intact fuselage. Based on a consideration of past accidents, experimental studies, and fuselage design, it is apparent that the fuselage rupture or opening represents the worst case condition and provides the most significant opportunity for fire to enter the cabin (Sarkos, 1988). It should be recognised that FAA cabin flammability standards for low heat release interior panels and seat cushion fire blocking layers were based on full-scale tests employing a fuel fire adjacent to a fuselage opening in an otherwise intact fuselage. By direct exposure of the interior materials to the intense thermal radiation emitted by the fuel fire, this type of scenario was representative of a severe but survivable fire condition against which to develop improved standards. However, in some crash accidents, the fuselage remained intact and fire penetration into the passenger cabin was the result of a burnthrough of the fuselage shell (Sarkos, 1990). Although the ignition of interior materials by an external fuel fire via fuselage burnthrough is expected to occur much later than when fuel fire impingement occurs directly through a fuselage opening, reported accident findings with fuselage burnthrough have produced fire fatalities but do not present a consistent behaviour. At least ten transport accidents involving burnthrough have occurred in the last 20 years, five in which the rapid fire penetration of the fuselage was a primary focus of the investigation, including Los Angeles 1972, Malaga 1982, Calgary 1984, Manchester 1985, and Anchorage 1987.

During an accident involving a Continental DC-10 at Los Angeles in 1978, a large fuel fire burned for 2 to 3 minutes before extinguishment by the Crash Fire Rescue personnel. Over this interval, the fuel fire did not penetrate and ignite the

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cabin furnishings, although there was some evidence of heat/flame damage at panel seams and along seat back cushions. It was clear from this accident that wide body transports (B-747, DC-10, and L-1011) could resist burnthrough for several minutes, as the fuselage walls of these aircraft are constructed of aluminium skin and heavy structural elements, along with thick thermal-acoustical insulation and honeycomb sidewall panels. Conversely, it was believed that narrow-body aircraft (B-727, B-737, MD-80) may allow flame penetration from burnthrough much more quickly because of the presence of aluminium sidewall panels, thinner thermal acoustical insulation, and in many cases a thinner aluminium skin (Sarkos, 1988). However, in the B-737 accident at Calgary in 1984, a fire resulted when the left engine failed and ignited the fuel released by the damaged nearby fuel tank. The fire was immediate and intensified as the aircraft was brought to rest almost 2 minutes later. Miraculously, 119 passengers and crew members were able to evacuate in an estimated 2-3 minutes, although portions of the cabin quickly filled with smoke when the exits were opened. The same could not be said of the B-737 accident in Manchester in 1985, which had a similar fire scenario as the Calgary accident, but in which 55 occupants perished from the effects of the fire. In this accident, it was believed that the external fire caused a very rapid burnthrough of the lower fuselage skin and quickly involved the cabin furnishings by gaining entry through the baseboard return air grilles (reference AAIB Report). During an accident involving a B-727 at Anchorage in 1987, a large fuel fire developed on the ground adjacent to the aircraft when it was accidentally towed into a loading walkway, causing massive fuel spillage due to a punctured fuel tank. Although a large section of the fuselage skin melted away from the ensuing fire, it did not spread into the cabin, indicating that in some cases the fuselage could act as an effective fire barrier. One key difference between the Manchester accident and both the Calgary and Anchorage accidents was the presence of wind directing the fuel fire flames against the fuselage, which could have aided the rapid fire penetration.

Although fire can penetrate into the passenger cabin by a variety of mechanisms, including the windows, the sidewall (above floor), cheek area (below floor), cabin floor, and baseboard return air grilles, there is no set pattern based on past accidents or experimental test data to indicate which area is the most vulnerable. Testing had been performed on the individual components (aluminium skin, windows, thermal-acoustical insulation, and sidewall panels) but had not been done on the complete fuselage shell system in which fire penetration paths and burnthrough times could be observed. For this reason, a test program was conducted to determine the mechanism and time framework for fire penetration into the cabin and ignition of the interior materials.

INITIAL FULL-SCALE BURNTHROUGH TESTS

To better understand the fuselage burnthrough problem, the FAA conducted a series of full-scale tests by subjecting surplus aircraft (DC-8 and Convair 880) fuselages to 400 square foot fuel fires. The fuel fires were set adjacent to the intact fuselage sections which were instrumented with thermocouples, heat flux transducers, and cameras to determine penetration locations, fire paths, and important event times. During the tests, each aircraft was divided into three sections by installing exterior barriers and internal partitions to confine the fire within the section being tested. Thus, each aircraft was tested three times (Webster, 1990). In the DC-8 tests, the aircraft was resting on its belly, simulating a crash with collapsed landing gear; the landing gear was extended during the tests on the Convair-880, as shown in figure 1.

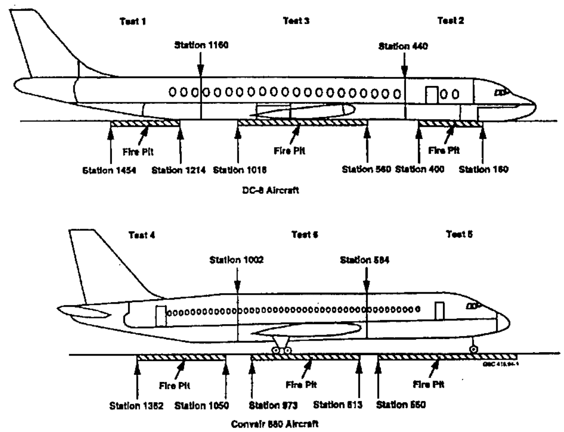

Figure 1

From the six tests, several major findings were concluded in terms of the likely entrance paths of the fire, and the time required to involve the cabin interior materials. The tests indicated that the aluminium skin provides protection from a fully developed pool fire for 30 to 60 seconds, and that the windows are effective flame barriers until they shrink and fall out of place due to the radiant heat of the fire, allowing flame penetration. These findings were consistent with data obtained during the investigation of the above mentioned accidents. The tests also highlighted the importance of thermal-acoustical insulation at preventing fire penetration. According to the tests results, the insulation can provide a significant delay of the burnthrough process, provided it remains in place and is not physically dislodged from its position by the updrafts of the fire. Several other findings were recognised, including the ability of the flames to gain access to the cabin by first penetrating into the cheek area, and then progressing upward through the floor return air grilles. Areas such as the empennage crawl-through that are not acoustically insulated were also found to be more vulnerable to burnthrough than other parts of the insulated fuselage, again illustrating the important role of the insulation. Additionally, the cabin sidewall is not thermally stressed as long as the acoustical insulation is intact, and the cargo compartment may provide a buffer zone protecting the cabin from burnthrough from under the aircraft. In terms of fire severity, it was determined that the aircraft with its gear extended is more vulnerable to burnthrough from a ground level pool fire than an aircraft resting on its belly, mainly because of the increased temperatures sustained at the higher locations in the fire.

DEVELOPMENT OF A FULL SCALE BURNTHROUGH TEST RIG

The next phase of the program involved the development of a test apparatus by which improvements could be evaluated, under realistic conditions. Prior to the construction and development of a testing apparatus, an effort was directed toward the use of actual fuselage sections for evaluating material and system improvements. Several 3.6m long sections of 707 complete with interior components were available to run successive tests on. The sections were well instrumented with thermocouples to determine burnthrough points and event times using a smaller fuel fire, measuring 2.4m by 3.0m, than in previous tests. The fuselage section was married to a full length 707 fuselage which was severed and separated, allowing insertion of the 707 test plug. Several other 3.6m sections of the fuselage would also be tested, in order to gain a sufficient level of confidence with this test arrangement. It became evident after the first test, however, that this arrangement required an excessive amount of man-hours to configure the test plugs to the point at which meaningful results could be obtained. The interior materials of the test plugs had to first be disassembled to allow thermocouple placement behind the skin and insulation. Along with the tedious job of re-assembly, additional work involving the proper sealing of the fuselage at the mating seams, combined with differences in each plug due to interior and exterior structure variations (cargo compartments, lavatories, galleys, exit doors, wing boxes, etc.) caused this approach to be abandoned.

Realistically, a full-scale test "rig" should allow repetitive testing in which singular components could be systematically evaluated. To accommodate this, a 6.0m long steel test section was constructed, and inserted into the 707 fuselage (figure 2). This section may be mocked-up with aluminium skin and accompanying insulation, floor and sidewall panels, carpet, and cargo liner. The mocked-up section extends beyond the 3.0m long fire pan, eliminating the mating problems experienced in the 707 plug tests. Measurements of temperature, smoke, and fire gases (CO, CO_2, and O_2) are taken inside the test rig, along with video coverage at several locations to determine exact burnthrough locations and times (figure 3).

FUSELAGE BURNTHROUGH TEST RIG

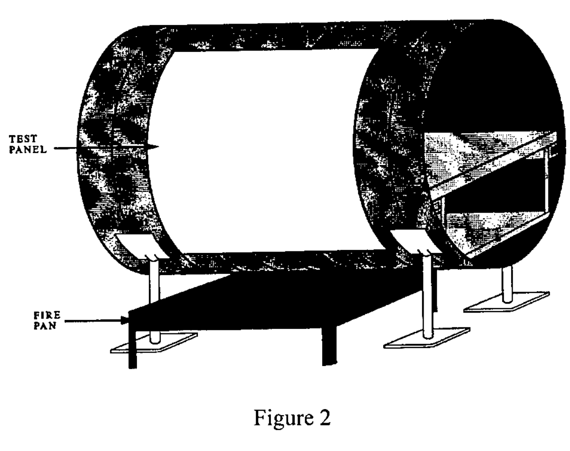

Figure 2

INSTRUMENTATION LOCATION

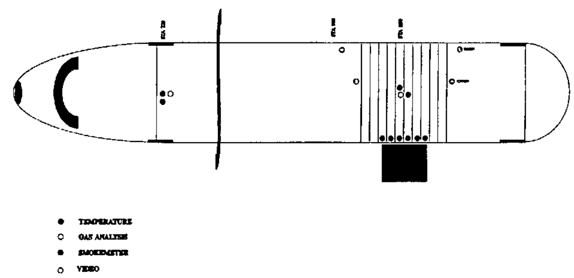

Figure 3

Prior to commencement of the mock-up tests, the apparatus was covered with Kaowool ceramic fibre blanket on the surface exposed to the fire; the Kaowool covered approximately half of the fuselage circumference, from centre bottom to centre top. The fuselage exterior surface was instrumented with thermocouples, calorimeters and radiometers in an effort to quantify this size fire at different locations with respect to the fuselage (figures 4, and 5).

CALORIMETER & RADIOMETER LOCATION

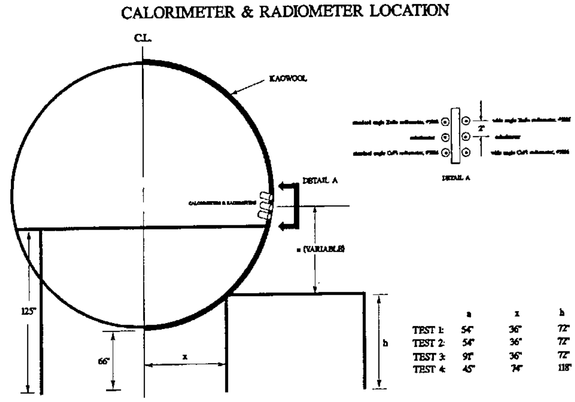

Figure 4

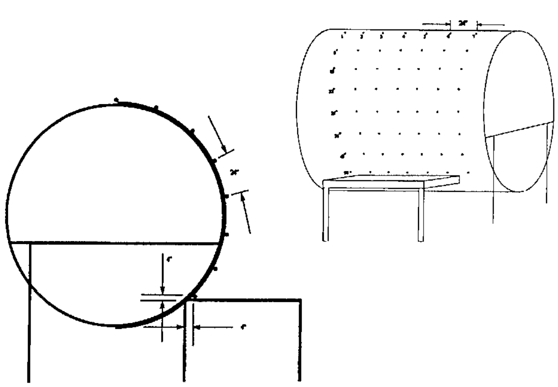

Figure 5

During past test programs, fires of this size were ignited next to fuselages at the cabin floor level, adjacent to a Type A opening to simulate an open escape exit or fuselage rupture. It was determined from earlier tests, however, that from a burnthrough standpoint, a more severe condition would result when the fire pan is slightly lower than the fuselage, allowing the higher temperatures of the upper flame area of the fire to come in contact with the fuselage lower area. Two fire pan locations were tested, and the more severe of these two was established as the standard fire pan placement for future material mock-up tests. These tests also provided information on the radiative and convective heat flux produced by this size fire. As shown in figure 6, the fuselage is subjected to a fire of between 160 and 180 kW/m^2 maximum, as measured by a Thermoguage calorimeter which measures the combined radiative and convective heat flux. By comparison, the Thermoguage radiometers measured the radiative heat flux only, which reached approximately 140 kW/m^2. The gradual but steady drop off in the heat flux occurs as a result of the devices becoming sooted by the fire. The differences in the radiative heat flux are the result of two types of radiometer window materials (ZnSe and CaF_2), and two angles of incidence (136° wide angle, 90° standard).

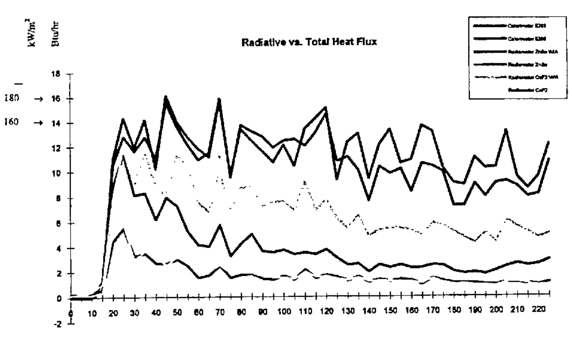

Figure 6

In order to evaluate potential improvements in materials and systems for better resistance to fuel fire penetration, a baseline test arrangement was established using in-service materials (figure 7). An aluminium skin section measuring 2.4m high by 3.6m wide was installed on the side of the test section. The panel consisted of two sheets of 1.6mm thick Alclad 2024 T3 aluminium, heli-arced together, each measuring 1.2m by 3.6m. The panel extended from the lower fuselage quadrant up to the window level, and was mounted to the test rig using steel rivets to reduce the potential for separation during testing. The remaining area of the fuselage was covered with 22 gauge sheet metal. The first several tests utilised custom-made insulation batting, consisting of Owens-Corning Aerocor fibreglass insulation encapsulated in Orcon brand heat shrinkable Mylar film, type AN-18R. The insulation and batting material was sized to fit in the spaces outlined by the vertical formers and the horizontal stringers of the test rig (figure 8). The insulation bats spanned the entire area of the aluminium skin (2.4m by 3.6m). In the cargo compartment, 0.33mm "Conolite" BMS 8-2A fibreglass liner was installed in both the ceiling and sidewall areas facing the fire, and held in place by steel strips of channel screwed into the steel frame of the test rig. An M.C. Gill "Gillfab" 4017 honeycomb floor panel measuring 1.2m by 3.6m was installed in the cabin floor area, and covered with FAA approved aircraft quality wool/nylon carpet. The remaining cabin floor area consisted of corrugated sheet steel. Interior sidewall panels from an MD-80 aircraft were used in some of the tests; the panels utilise an aluminium substrate and do not meet the current FAR's regarding heat release rate. The outboard cabin floor area contained steel plate with 76.2mm diameter holes to simulate the venting area between the floor and cheek area. Additionally, an aluminium mesh was installed below the sidewall panels to simulate the baseboard return air grilles (figure 9).

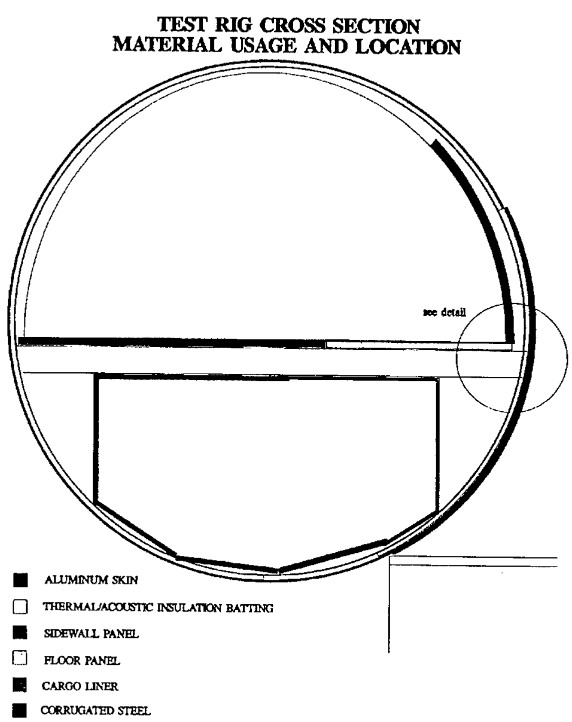

Figure 7

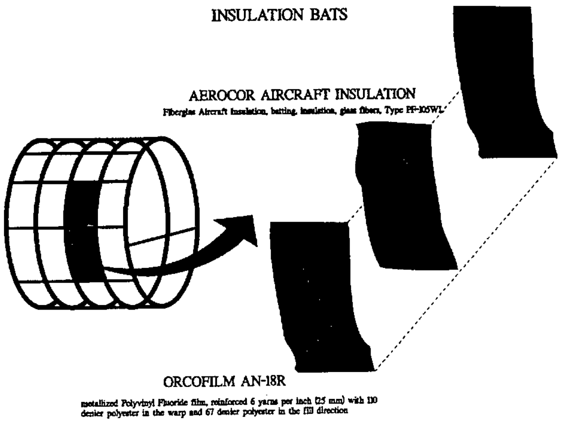

Figure 8

Fuselage Sidewall and Floor Cross Section

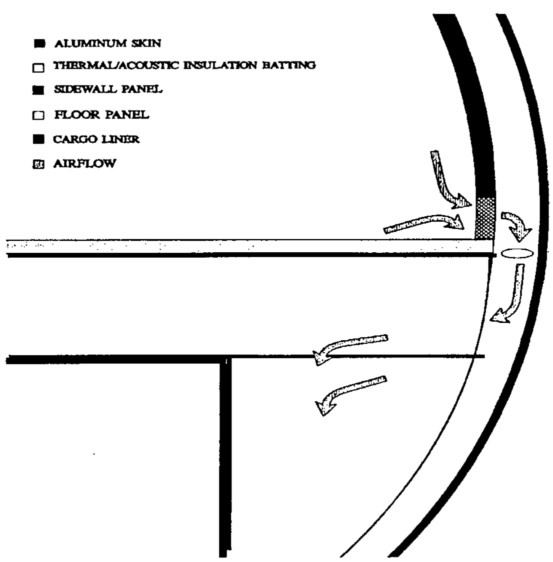

Figure 9

Initial Baseline Test Results

During the first test, the fire burned through the aluminium skin within 30 seconds, and quickly displaced or penetrated the thermal-acoustical insulation bats, allowing flames to enter the cheek area within 40 seconds. The fire intensified, and ignited and burned through the cargo liner into the cargo compartment in approximately 60 seconds. Concurrently, the fire penetrated the cabin through the sidewall, as well as the floor return air grilles. The actual point of first penetration into the cabin was difficult to decipher, since the fire propagated both the sidewall panels and floor return air grilles within a short time of one another. The burnthrough location(s) were masked somewhat by the placement of sidewall panels over the insulation in the cabin. Early indications pointed to the lack of complete coverage by the thermal-acoustical insulation, which had been attached to the test rig by loosely packing it into the spaces between the stringers and formers, and duct taping all edges. Since a major objective is to determine the effectiveness of the thermal-acoustical insulation when it is not physically displaced, an effort was given to better secure the batting material. During the next test, in which the material configuration was identical to the first test, the insulation bats were oversized slightly and were clipped onto the steel formers using spring steel locking jaw clips. The excess insulation material was wrapped over the edges of the curved steel-channel formers, and clamped in place approximately every 40 cm to prevent the insulation material from becoming easily displaced.

Although the progress of the fire appeared to be slowed during the second test, data revealed that the temperature and gas build-up within the cabin occurred nearly identically to the first test. The thickness of the insulation became the focus for the next test, as there was some indication that the one inch thickness was unrealistic for this area of the fuselage. An inspection of several surplus fuselages revealed that the insulation was at least several inches thick in the sidewall area (the insulation actually becomes much thinner at the extreme lower section of the fuselage, as the acoustical requirements are not nearly as stringent as in the cabin area). The thickness of insulation varies between aircraft, but was found to be at least several plies thick in the areas of the fuselage where the fire had penetrated during the first two tests. For this reason, a third test was run using three ply thermal-acoustical insulation inside each insulation bat; the spring clamps were again used to hold the insulation in place. In order to better investigate the burnthrough point and time, the sidewall panels, cargo liner, and floor panels were not installed. The third test proved to be much more realistic in terms of burnthrough time when compared to the previous surplus airframe tests.

Future Test Work in Full-Scale Apparatus

From the results of the initial full-scale burnthrough tests, as well as the several tests completed in the burnthrough test rig, it is evident that the aluminium skin can be considered a given, providing at least 30 seconds of protection prior to melting and subsequently allowing flame impingement on the thermal-acoustical insulation. The material types and thicknesses of aluminium skin currently in use will likely be used in next generation aircraft to a large extent. This leaves the focus of the burnthrough problem between the time the fire melts through the skin, until the time it first enters the cabin. Attention has therefore been directed towards the thermal-acoustical insulation, both the method of attachment of the insulation and the flame resistance of the insulation itself will be studied. Currently, there are several different methods of insulation bat attachment, most of which consist of thermoplastic washer type fasteners. In terms of flame resistance of the insulation batting, there are a variety of new technology materials that can withstand elevated temperatures typical of a large fuel fire for extended periods of time. Results of tests with these new materials are presented later in this paper. After the insulation is penetrated the least resistant path for flame entry into the cabin is via the air return grilles. This was evident in the earlier full-scale burnthrough tests (Webster, 1994). Intumescent paint may be a simple concept for delaying grille penetration.

Another area that will be studied closely is the burnthrough resistance of a composite skin fuselage. The use of composites in transport category aircraft has grown steadily due to the high strength and low weight associated with them. The fuselage skin of the High Speed Civil Transport (HSCT)

could feasibly be constructed of a composite material, so an assessment of it's capabilities when exposed to large area fires must be addressed. From a burnthrough standpoint, a composite fuselage would likely offer greater burnthrough protection to a large external fire than aluminium. However, there is concern over the potential for toxic and combustible gases being released during flame exposure, which could present a severe hazard to the escaping occupants. It will be possible to evaluate this scenario using the full-scale test rig by replacing the aluminium skin with composite structure and measuring the resultant gases within the cabin.

DEVELOPMENT OF A MEDIUM SCALE BURNTHROUGH TEST RIG

During the early phase of the current joint research program, it was determined that the development of a small or medium scale burnthrough test facility could be beneficial in investigating the problem of burnthrough. A laboratory test facility which could replicate the full-scale conditions would allow for quick and inexpensive testing of improved materials and/or systems, and also serve as a screening device for evaluating new materials under consideration.

Definition of Heat Source. The search for information to define the heat source was concentrated on previous published test work, studies of postcrash fires, and the study of general pool fires. The literature survey carried out with the assistance of the CAA and the FAA produced a number of articles that related to the fire testing of aircraft and hydrocarbon pool fires. A review of data produced a wide range of values for the temperatures and heat fluxes developed by hydrocarbon pool fires, therefore the selection of a representative fire was difficult. When proposing the upper values of the representative heat source, the mean of the highest temperatures and heat fluxes from the previous experimental data were considered. The values are given below:

Temperature	1150°C
Heat Flux	160 kW/m^2
Gas velocity	2 m/s at 1150°C
Fire status	Fully developed
Profile of fire curve level	Instantaneous rise to maximum

The values agree with the values that FTC have previously experienced in fire scenarios relating to both the aircraft and general industry. Lower levels of heating were also considered, and were intended to represent a pool fire at a distance from the fuselage. However, in the previous studies there was no reference to a lower heating level, so it was decided that the maximum duration of heating required would be 10 to 15 minutes, at the end of which aluminium skin should have just melted. The lower level was therefore taken as the temperature at which the aluminium skin would typically melt.

Temperature	650°C
Heat flux	42 kW/m^2

It was expected that FAA test results would fall within the upper and lower levels as previously defined. Whilst defining the heat source an opportunity arose to conduct an indicative test on a commercial aluminium panel. The panel started to burn through after 80 seconds with a furnace aperture temperature of 950°C, demonstrating that the basic principle of using a furnace to simulate a pool fire scenario was a sound one.

Burnthrough Apparatus

After considering the published test data as well as previous testing experience, it was decided that the best method of producing a controlled and repeatable heat source was to design and build a dedicated gas fire test unit (figure 10). The basic system consists of a mild steel box, internal dimensions 2m by 2m by 1.5m, lined with ceramic fibre and powered by four 300 kW propane burners which fire tangentially to ensure that energy is transferred efficiently to the furnace wall. The floor of the furnace is brick-lined to provide the required heat energy, both convective and radiative, in the correct proportions. The air and propane gas supply are driven to the furnace by a fan and a pressurised gas supply, respectively. The roof of the furnace incorporates a manually operated sliding lid which when rolled back reveals a 1 meter square aperture on the top of the furnace. The sliding lid section has a plug type sealing action onto a 25mm ceramic fibre gasket to ensure that no hot gases leak out during the furnace warm up period. The test sample is supported over the sliding lid in the roof section. When the furnace is heated up to temperature and soaked, the insulated lid is rolled back, allowing instantaneous thermal insult to the test sample for the duration of the test. The results show that this method of storing energy and then releasing it provides the rise in a repeatable form.

Medium Scale Burnthrough Test Facility

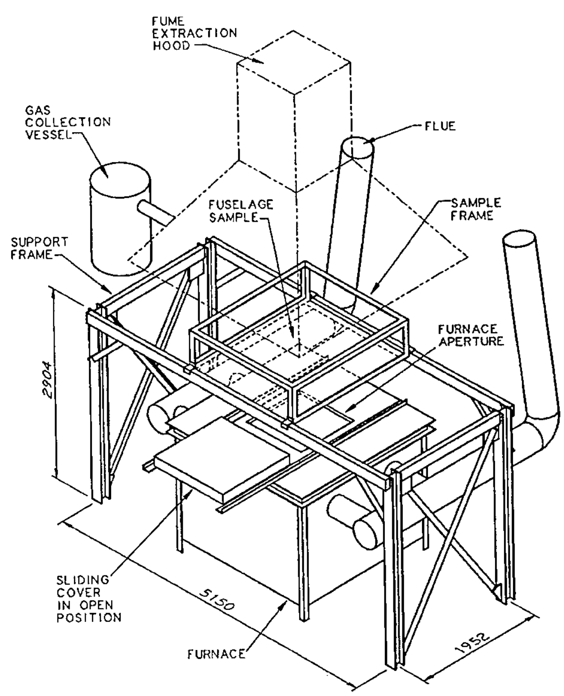

Figure 10

Commissioning

A primary objective of building the test apparatus was to produce a heat source that simulated a pool fire without the inherent fluctuations in temperature and heat flux of a real pool fire. A number of trials were devised to determine if the test apparatus could yield reproducible results while operated between the upper and lower test limits. Initial results demonstrated a significantly better level of reproducibility when compared to test results from real pool fires. The furnace temperatures were being held to within 2% of the desired value at 1150°C, which compared favourably with observed pool fire temperature fluctuations of up to 40%; the associated heat fluxes were reproduced with a level of repeatability of +/- 12% at the higher temperatures.

Early Burnthrough Trials

During the commissioning phase of the program some preliminary burnthrough trials were conducted to compare burnthrough times of the test apparatus with the FAA full scale test results. The comparison revealed a marked difference in burnthrough times, as the test apparatus samples required 2 to 3 times greater the amount of the full-scale duration to completely burn through. After re-checking and confirming the performance of the burnthrough facility, the values of temperature and heat flux being measured were actually in excess of those measured in the FAA pool fire. Subsequent trials conducted on a small number of aluminium samples yielded burnthrough times of the order of 180 seconds. As before, these results were not as expected, since previous FAA full scale tests produced burnthrough in 26 seconds on identical samples for similar values of temperature and heat flux.

At this stage it was suggested that this apparent discrepancy in burnthrough times could be due to soot being deposited on the sample in the early stages of the fire, leading to an increase in surface emissivity. This was in contrast to the gas powered facility where the clean burning nature of the fuel meant that no soot was produced. An increase in surface emissivity would allow a greater amount of radiant energy to be absorbed, resulting in shorter burnthrough times. Having established theoretically that soot deposition could be a major influence on the fuselage burnthrough time, more trials were carried out using 0.7mm aluminium panels, identical to those used during the commissioning phase. The bare aluminium test sample burnt through in 58 seconds at a height of 50mm above the aperture when subjected to a temperature of 1150°C and a heat flux of 200 kW/m^2. An identical panel was coated with a thin layer of soot from an acetylene torch and tested in the same position; burnthrough occurred in 8 seconds. At this stage the main program was postponed in order to more closely investigate the effect of soot deposition on aluminium panels in the early stages of a pool fire, and its relationship to burnthrough time.

Soot Deposition Trials

A simple sooting rig was constructed and a number of aluminium panels of different thicknesses were exposed to a small pool fire for different lengths of time. A clean aluminium panel has an emissivity of approximately 0.10. When exposed to the small pool fire for at least 30 seconds, the emissivity of the test sample increased to a value between 0.50 and 0.80. The separate sooting trials showed that surface emissivity is dependent on the time that a surface is exposed to an adjacent enveloping pool of fire. The pool fire used in the sooting investigation was smaller than a typical postcrash fuel fire to enable a range of emissivities to be obtained so that a relationship to burnthrough time could be established. Although the surface emissivity of the aluminium increased to a value between 0.50 and 0.80 after 30 seconds exposure, this may occur after only a few seconds during a large scale pool fire.

A series of burnthrough trials were conducted using the sooted aluminium panels to develop a relationship between emissivity and burnthrough time. At low surface emissivities, burnthrough time decreases rapidly as surface emissivity increases, but once the surface emissivity approaches 0.60, any further increase subsequently produces a very small decrease in burnthrough time. For this reason, burnthrough times are very similar for surface emissivities of 0.60 to 0.90. A plot of surface emissivity vs. burnthrough time is shown in figure 11.

Surface Emissivity Vs Burnthrough Time

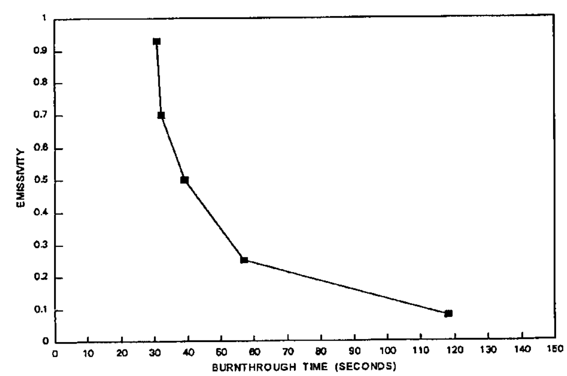

Figure 11

Cold Sooting Facility

It was concluded that for the test apparatus to accurately represent a postcrash pool fire, the emissivity of the sample must be controlled and therefore, all samples need to be pre-conditioned to an appropriate emissivity value before testing. It was necessary to develop a method for sooting samples without the risk of heat damage occurring, so that a wide range of materials could be tested. A technique was developed which enables the soot to be deposited without the need for exposure to intense fire conditions, hence the term "cold sooting" (figure 12).

Cold Sooting Rig

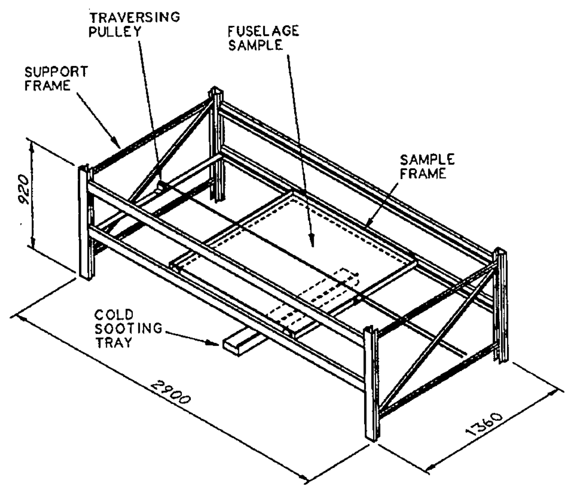

Figure 12

A frame is laid across the rig's modular racking system into which the sample is placed. The sample frame has a runner at each corner that enables the frame to traverse smoothly along the racking system. A wire and pulley arrangement allows the sample frame to be moved along the length of the rig from outside the enclosure. A tray is centrally positioned underneath the rig and contains a strip of ceramic fibre material soaked in kerosene which acts as a wick. A cover is positioned over the tray so that only a narrow strip of material protrudes, which is then made to burn.

Investigation of Burnthrough Parameters

The next phase of the program sought to identify the parameters most likely to have an effect on burnthrough time. The parameters chosen were surface emissivity, material thickness, external paint, structural features and the presence of insulation. Once these features were identified, a series of burnthrough trials were conducted in an attempt to assess the affect each had on burnthrough time. Several conclusions emerged from this phase of work.

The importance of surface emissivity has already been covered. As expected, burnthrough time increases as material thickness increases. A 0.9mm aluminium panel with a surface emissivity of 0.64 burnt through in 24 seconds. A 2.0mm aluminium panel with an identical surface emissivity burnt through in 43 seconds. The presence of paint covering on an aluminium panel does not necessarily affect burnthrough time. The change of surface emissivity, if any, resulting from the application of the paint is the important consideration. Aluminium panels containing typical structural features burnt through between 5 and 10 seconds slower than similar panels with no additional features. The difference can be attributed to the increase in structural integrity achieved by the presence of a double thickness of aluminium in the region of the feature. The presence of the insulation material seems to have little effect on burnthrough time for the aluminium panel.

Burnthrough of Fuselage Systems

This phase of the program sought to build on the burnthrough tests carried out in previous phases. The work was comprised of the following: a comparison of insulation materials, the burnthrough of existing fuselage systems, and an investigation into the performance of new materials. In addition to the determination of burnthrough times, the objective of this phase was to investigate the impact smoke emission and toxic gas release may have on occupant survivability.

Toxic Gas and Smoke Measurement

For the measurement of toxic gas and smoke emissions, several modifications were made to the burnthrough apparatus including a furnace hood extension used to contain any gas or smoke release, and a small collection hood positioned centrally above the furnace aperture which is connected by a length of stainless steel pipe to a cylindrical stainless vessel. Both the lengths of pipe and the vessel are insulated and maintained at a temperature above 100°C by means of resistive heating element. A small pump draws gas into the collection hood along the pipe and into the collection vessel, from which gas samples are drawn off for measurement. Measurement of specific toxic gases is done using a gas analyser which combines Fourier transform infrared spectroscopy (FTIR) with photo-acoustic spectroscopy (PAS). It can be used to determine the composition of gas samples and can also be used to make repeated concentration measurements for up to 7 gases simultaneously. Almost all gases that absorb infrared light can be measured. The gases chosen to be monitored were carbon monoxide, carbon dioxide, hydrogen chloride, hydrogen bromide, and hydrogen fluoride. In addition, the concentration of oxygen is measured continuously throughout the test using a combustion efficiency analyser for on the spot gas analysis. It consists of an instrument and an analyser unit which evaluates and calculates the measured data. A pump draws the gas to be examined via a probe, which is cleaned by means of a condensate separator and a course filter and is then supplied to the incorporated oxygen measuring cell.

To quantify the smoke release from a particular sample, the following arrangement exists. On one side of the central flue a light source is positioned and on the opposite side of the flue there is a photo cell. The amount of light detected by the cell is represented as a voltage which is directly proportional to the light intensity. The amount of smoke released is then measured as the percentage reduction in light transmission.

Comparison of Insulation Materials

During this phase of the program, an attempt was made to compare different types of in-service encapsulated insulation. The materials selected were glass fibre, carbonaceous fibre, and polyimide foam. All insulation systems tested displayed both superior and inferior qualities in a variety of comparisons. It was observed that the presence of insulation can delay flame penetration following skin melting from between 20 seconds to 8 minutes, depending on the type. In order to assess the suitability of the insulation materials tested, a clearer indication of the criteria for failure needed to be established, whether it be burnthrough resistance, loss of structural strength, toxic gas and smoke emission or more likely a combination of all these.

Burnthrough of Existing Fuselage Systems

The majority of test work to date had involved testing flat aluminium panels, whereas in this phase burnthrough tests were conducted on actual fuselage sections. In addition to the outer shell, other fuselage components were tested, including insulation, interior sidewall panels, corrosion inhibitors, and passenger windows. For most of the burnthrough tests, the aluminium skin melted after 35-45 seconds. The presence of fibreglass insulation appeared to delay burnthrough to the inner face by an additional 60 seconds. During tests involving passenger windows, the window tended to be the weakest part of the structure, and failed to remain in place after less than a minute. The window seal burnt, the aluminium around the window distorted, and the window dropped out.

The use of corrosion inhibitors emerge as an area of concern. Corrosion inhibiting compounds commonly known as "goop" are hydrocarbon based water displacing compounds and tend to be highly flammable. Airframe manufacturers and maintenance facilities apply varying quantities of these anti-corrosion compounds to the interior of the fuselage. The Test Work demonstrated the tendency of these compounds to cause the cold face of the test sample to flash with flames within 15 to 20 seconds of exposure to representative conditions. Such an effect could in turn cause the insulation bats or any dust/debris to ignite and propagate a fire before the exterior fire has actually penetrated the fuselage skin. The interior panels tested performed poorly, giving off dense black smoke immediately following exposure of the back face to the radiant heat, which was typically 100 seconds.

As part of an earlier phase of the program, tests were conducted on a cabin floor material. The composite panel was a structural grade laminate consisting of Nomex aramid fibre/phenolic resin core faced on both sides, with unidirectional cross-plied glass fibre skins. When subjected to conditions representative of a post crash fuel fire, huge plumes of dense black smoke were given off within seconds, for the duration of the test. In a real crash situation, it may be unlikely that the cabin floor receives the full effect of the fuel fire, but the performance of the floor material suggests that an investigation into the fire properties of these materials is necessary.

INVESTIGATION OF NEW MATERIALS

Aluminium alloy is by far the most common material currently used in aircraft structures, and will likely remain for a number of years. However, advanced alloys, metal composites, and reinforced plastics may make progressively larger inroads. This section sought to investigate the behaviour of materials currently being produced or considered as replacements for existing aluminium alloys. Two types of materials were tested: an 8000 series aluminium alloy containing approximately 2.5% lithium (in addition to the usual constituents), and various fibre-metal laminates consisting of alternate layers of thin, high strength aluminium alloy sheets with fibre-impregnated adhesive.

Initial results indicated the aluminium/lithium alloy provided slightly greater burnthrough resistance than existing aluminium alloys, by approximately 20%. Both fibre-metal laminate configurations appeared effective in delaying the penetration of fire, but within the first minute of the test, substantial amounts of smoke were produced, making it impossible to determine how much of the structural integrity of the panel remained. The burnthrough resistance of this system was clear however, as it resisted penetration for 3-4 times longer than conventional aluminium alloys.

As previously stated results of both full scale and medium scale tests have shown that the aluminium skin can consistently provide at least 30 seconds of protection prior to melting. Once the aluminium has melted this allows flame impingement upon the insulation system. The material types and thicknesses of aluminium skin currently in use will continue to be used even in the next generation of aircraft.

Therefore the focus of the current work on burnthrough is on extending the time from when the aluminium skin melts until the time when fire enters the cabin. Specifically attention is being focused on thermal-acoustic insulation which Test Work has demonstrated can be an effective fire barrier so long as it remains in place. For this reason, both the method of attachment and the flame resistance characteristics of the insulation are being studied.

Recent results from the investigation of advanced insulation material

All the tests pieces were made up of two components. An aluminium panel and an insulation blanket.

The aluminium was 1.6mm thick and was to the specification alclad 2024-T3. All the aluminium panels were preconditioned to an appropriate surface emissivity using the cold sooting facility and procedure as previously described. For each test five thermocouples were positioned on the back face of the aluminium.

The insulation material tested comprised three types and two thicknesses. The three types of material tested were Schuller Microlite AA, Orcon FB-300 and Orcon FB-300-SA.

Schuller Microlite AA is a fibre glass material with a density of 6.7 kg/m^3. This insulation was tested at both 2" (50.8 mm) and 3" (76.2mm) thicknesses.

Orcon FB-300 and FB-300-SA are Orcon product designations for insulation batting made using RK Carbon Fibre Curlon® Fibres. Curlon® is comprised of heat treated oxidised polyacrylonitrile fibre and is similar in appearance to fibre glass but black in colour. The FB-300-SA type has superior acoustical properties. Both materials have a density of 5.5 kg/m^3. The FB-300 was tested at 3" (76.2mm) thickness and the FB-300-SA at 2.5" (63.5 mm) thickness.

All the insulation materials tested were sealed in water resistant polymer bags manufactured by the Orcon Corporation. For tests 1-3 and 5 the covering film used was Orcofilm® AN-18R, which is a metallized polyvinyl fluoride film, reinforced on one side with polyester yarns. For tests 4,6 and 7 the film used was Orcofilm® KN-80 Kapton which is a polyimide film, reinforced on one side with nylon yarns.

For each test the insulation blankets were positioned on the back face of the aluminium panel and five thermocouples were positioned on the back face of the insulation blanket. In addition a thermocouple was positioned 100mm above the

centre of the insulation blanket to provide a cold side temperature measurement.

All the test pieces were tested in the burnthrough facility as previously described.

A summary of the test results is provided in Table 1.

Aluminium

As can be seen from the test results the burnthrough time for the aluminium tested is consistently in the region of 35 seconds with the exception of two tests. This burnthrough time is as expected and correlates well with earlier test work.

Insulation

At 2" (50.8 mm) thickness the fibre glass encased in polyvinyl fluoride film provided an additional 19 seconds protection following the burnthrough of the aluminium, giving a burnthrough time for the system of 55-56 seconds (Test 1).

At 3" (76.2mm) thickness when again encased in polyvinyl fluoride film the protection afforded was an additional 18-21 seconds, giving a burnthrough time for the system of 55-60 seconds (Test 2). Its also worth noting that once burnthrough had occurred the 3" (76.2mm) fibre glass lasted longer than the 2" (50.8 mm) before collapsing completely. At 3" (76.2mm) thickness when encased in polyimide film the insulation provided an additional 43 seconds protection, giving a system burnthrough time of 78 seconds (Test 7).

For tests 1 and 2 the insulation was laid across the aluminium and weighted down at all four sides with mild steel angle. As a result of test 4A it was concluded that this method of fixing, while suitable for tests of short duration, was unsuitable for tests involving insulation which survived for a number of minutes.

So as a result of working closely with the FAA it was decided that in order to keep the insulation in place, spring steel locking jaw clips would be used along the perimeter of the test sample. In this way provided the insulation test piece is large enough to overlap the test frame the test piece will remain in place for the duration of the test. The positioning of the jaw clips is such that they do not interfere with the test itself.

The results from the tests on the Curlon® fibre insulation were very impressive.

At 3" (76.2mm) thickness the Orcon FB-300 encased in polyvinyl fluoride film resisted burnthrough for an additional 120 seconds following the burnthrough of the aluminium, giving a system burnthrough time of approximately 150 seconds (Test 3). When encased in polyimide film the insulation provided an additional 360 seconds protection giving a system burnthrough time of approximately 390 seconds (Test 4B).

In test 4A the system burnthrough time was approximately 300 seconds, 90 seconds less than in test 4B. This was due to the method of attachment of the insulation system to the test frame as previously discussed. In test 4A the mild steel angle was ineffective in holding the insulation in place for the duration of the test.

At 2.5"(63.5 mm) thickness the Orcon FB-300-SA encased in polyvinyl fluoride film resisted burnthrough for an additional 240 seconds following burnthrough of the aluminium, giving a system burnthrough time of approximately 270 seconds (Test 5). When encased in polyimide film the insulation provided an additional 510 seconds protection giving a system burnthrough time of approximately 540 seconds (Test 6).

Bagging Film

For the tests using polyvinyl fluoride film as the bag material for both the fibre glass and Curlon® insulation the results were not as impressive as when using polyimide film.

Considering first the fibre glass insulation. With polyvinyl fluoride film 3" (76.2mm) fibre glass provided an additional burnthrough time of 19 seconds with polyimide film the time was 43 seconds, more than double.

Equally impressive results were obtained with Curlon® insulation. With polyvinyl fluoride film 3" (76.2mm) FB-300 provided an additional burnthrough time of 120 seconds with polyimide film the time was approximately 360 seconds almost three times the protection. With polyvinyl fluoride film 2.5" (63.5 mm) FB-300-SA provided 235 seconds additional protection and with polyimide film 515 seconds, again more than double.

Once burnthrough of the aluminium had occurred the polyvinyl fluoride film set alight allowing flame propagation to the cold side and was quickly consumed. In contrast the polyimide film displayed excellent fire resistance. No flaming occurred and the film remained in place on the cold side for the duration of the tests.

CONCLUSIONS

Aluminium

When exposed to conditions representative of an external jet fuel fire typical aircraft grade aluminium can only provide 30-40 seconds protection before burnthrough occurs.

Insulation

Typical aircraft grade fibre glass insulation when encased in polyvinyl fluoride film whether 2" (50.8 mm) or 3" (76.2mm) thickness can only be expected to delay burnthrough by approximately 20 seconds. When the bagging material is polyimide film this time increases to approximately 40 seconds.

Curlon® fibre insulation displays excellent burnthrough resistance characteristics. Orcon FB-300 at 3" (76.2mm) thickness when encased in polyvinyl fluoride film and then polyimide film delayed burnthrough by approximately 120 and 360 seconds respectively, six and nine times longer than conventional insulation. Orcon FB 300-SA at 2.5" (63.5 mm) thickness when encased in polyvinyl fluoride film and then polyimide film delayed burnthrough by 240 and 520 seconds respectively, twelve and thirteen times longer than conventional insulation.

Bagging Film

Polyimide film when compared to polyvinyl fluoride film demonstrates exceptionally good flame resistance characteristics. When used instead of polyvinyl fluoride film on insulation blankets the burnthrough resistance of the blanket appears to be increased at least two-fold. The inner face of polyimide film remains intact for longer than polyvinyl fluoride

film which tends to flame briefly and shrink. In this manner polyimide provides a better smoke and toxic gas barrier.

Comparison of Full Scale and Medium Scale Test Results
Table 2 allows comparison of recent full scale FAA test results with those obtained at medium scale.

FUTURE CONSIDERATIONS

The medium scale burnthrough facility funded by the CAA and developed by Faverdale Technology Centre replicates the conditions representative of a post crash jet fuel fire. It allows for quick and inexpensive testing of improved materials and systems, and as such can serve as a screening device in evaluating new materials.

The recent Test Work has focused on flat aluminium panels 1.2m x 1.2m and insulation blankets of a similar size. The test results provide a very good indication of the material burnthrough characteristics. However it would be unwise to interpret these results in isolation and extend their significance beyond that of a material test.

In the full scale burnthrough tests the insulation material is secured in place around the perimeter using mechanical spring steel clips attached to steel frames. An insulation blanket in material tests may appear to delay burnthrough by 5 minutes however in reality after such exposure to a fuel fire the aluminium fuselage structure may well have collapsed reducing the effectiveness of any insulation system. Even if the fuselage shell remains intact the method of attachment of the insulation blankets to the fuselage frame is critical. The insulation cannot provide a barrier to burnthrough if it is no longer there.

The medium scale burnthrough test set up can be improved upon to more closely represent a real aircraft. Such measures may involve stylising an aluminium panel with the necessary frames and stringers thereby enabling the mechanical integrity of the insulation attachment and joints to be accessed.

It is also necessary to continue improving the full scale test to more closely represent a real aircraft and fire condition. Such improvements will involve using aluminium frames and stringers and more realistic methods of insulation attachment.

Finally I would like to draw your attention to a very positive development for the enhancement of burnthrough safety. In the past there has been criticism of the time it takes to get new safety features installed in aircraft. In part this is due to the time it takes for manufacturers to become familiar with the issues following research conducted by Aviation Authorities. With new concepts there is also the added risk that predicted costs may be prohibitively high because the concept has not been "production engineered" and cost benefit calculations prevent the introduction of the safety feature, even though eventual production costs may be lower. Clearly for the Authorities and the Industry to work together from an earlier stage in the research and design process would be advantageous.

In Europe an international industrial consortium led by Airbus Industrie will be proposing an Industrial Materials and Technology research project to the European Commission. This project will build on the work initiated by the Aviation Authorities. The objective is to identify materials and processes capable of substantially improving burnthrough resistance and also capable of being introduced to aircraft production lines in a timely and economical manner.

In a recent paper Theo Klems of Airbus Industrie stated

"Accidents and tests have shown that the aluminium skin currently used on production aircraft fuselages can burnthrough within 60 seconds. Once burnthrough occurs conditions in the cabin rapidly become unsurvivable. There are no international regulations or internationally recognized techniques for the assessment of burnthrough resistance.

Fuselage burnthrough resistance has been quantified as an important safety issue and that was the reason for the CAA to initiate a European programme which is composed of European airframe manufacturers, European Airworthiness Authorities and European Test Institutes.

The objective of the programme will be to identify the current weaknesses with regard to the penetration of the fuselage. Further research and development will lead to an understanding of the failure mechanisms involved in burnthrough. Design principles and methods will be established, a small scale test method suitable for industry will be developed and with the establishment of specifications and design guidance the optimum design and materials selected

The consortium will develop a test method that will identify new materials, and enable the introduction of new design principles and design methods which will make significant improvements to cabin safety."

Table 1 Insulation Materials Tested in CAA Programme

Test No.	*Insulation Material*	*Insulation Thickness (mm)*	*Insulation Density (kg/m³)*	*Film Material*	*Perimeter Clips*	*Burnthrough Time Aluminuim (sec)*	*Burnthrough Time Insulation + Film (sec)*	*Burnthrough Time System (sec)*
1A	Schuller Microlite AA	50.8	6.7	AN-18R	×	37	19	56
1B	Schuller Microlite AA	50.8	6.7	AN-18R	×	36	19	55
2A	Schuller Microlite AA	76.2	6.7	AN-18R	×	34	21	55
2B	Schuller Microlite AA	76.2	6.7	AN-18R	×	42	18	60
7A	Schuller Microlite AA	76.2	6.7	KN-80	✓	35	43	78
3A	Orcon FB-300	76.2	5.5	AN-18R	✓	29	120	≈150
4A	Orcon FB-300	76.2	5.5	KN-80	×	35	270	≈300
4B	Orcon FB-300	76.2	5.5	KN-80	✓	35	360	≈390
5A	Orcon FB-300-SA	63.5	5.5	AN-18R	✓	35	240	≈270
6A	Orcon FB-300-SA	63.5	5.5	KN-80	✓	35	510	≈540

Table 2 Materials Tested in FAA Burnthrough Test Programme

Test No.	*Date*	*Insulation Material*	*Insulation Thickness (mm)*	*Insulation Density (kg/m³)*	*Film Material*	*Additional Barrier*	*Burnthrough Time (sec)*
7	7.12.95	Schuller Microlite AA	50.8	9.6	AN-18R	N/A	70
8	15.12.95	Schuller Microlite AA	76.2	9.6	AN-18R	N/A	92
9	20.12.95	None	N/A	N/A	N/A	N/A	50
10	25.1.96	Orcon FB-300-SA	76.2	5.5	AN-18R	N/A	>300
11	8.2.96	Orcon FB-300	76.2	5.5	AN-18R	N/A	>300
12	29.2.96	Orcon FB-300-SA	76.2	5.5	KN-80	N/A	>300
13	4.4.96	Schuller Microlite AA	76.2	9.6	AN-18R	Nextel Fiber	>300
14	11.4.96	Schuller Microlite AA	76.2	9.6	KN-80	N/A	240
15	18.4.96	Orcon FB-300-SA	38.1	5.5	AN-18R	N/A	380
16	6.5.96	Orcon FB-300-SA	76.2	5.5	KN-80	N/A	>480
17	23.5.96	Schuller Microlite AA	76.2 & 38.1	6.7	KN-80	N/A	120
18	5.6.96	Schuller Microlite AA		6.7	AN-18R & KN-80	N/A	

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DISCUSSION - PAPER NO. 24

A. Carter (Question)

1) In your Paper, you quote heat flux values of between 42 and 200 kw/m^2. What heat flux did you finally select for your rig?

2) How does this compare with the value of 105 kw/m^2 prescribed in FAA AC 20-135, which simulates torching flames associated with power plant failures (oil and fuel lines)?

N.J. Povey - Author/Speaker (Response)

1) The facility has been characterised for heat fluxes of up to 160 kw/m^2 (ref. page 6). 160 kw/m^2 is the appropriate heat flux for the testing of external pooled fuel fire on the aircraft skin. For other components, e.g. the under side of floors, a lower value will be used. The exact value will be determined by full-scale tests.

2) In determining the value of heat flux appropriate, a major study of the literature was undertaken. From measurements of large pooled fuel fires in aviation and petro-chemical industries, it was determined that 160 kw/m^2 was appropriate as a maximum. One of the reasons why this figure differs from that used in AC 20-135 is that the large pooled fuel fire is associated with large quantities of smoke due to fuel rich combustion. It is these smoke particles which contribute to the very high radiative component of the total heat flux. The radiative component in very large fires can be as high as 80%.

G. Roebroeks (Question)

To my knowledge, the interior of the fuselage (baggage racks, composite side panels, floors, chairs, etc..) is attached to the aluminum skin structure (skin, stringers and frames). From your video, I understood that the insulation material is on the inside of the skin structure. If you are no longer able to carry the weight of the fuselage interior in case of an outside fire melting away part of the fuselage skin structure (say skin material), what is in that case the benefit of the interior insulation material?

N.J. Povey - Author/Speaker (Response)

It is only necessary to provide a few minutes of additional escape time in order to have a very large life-saving potential (Ref. CAA Paper 93010 - Safety Benefit Analysis of Cabin Water Spray Systems). In aircraft accidents, the fuselage skin may melt or burn through quickly, but the stringers and frames remain for long periods. Many post-accident photographs show a skeleton of stringers and frames remaining. If collapse of the fuselage does occur, it is well after survival is possible within the cabin. By working closely with aircraft manufacturers, it is the intention to pay careful attention to the detailed design of insulation attachment, in order to maximise burnthrough resistance.

TITANIUM FIRE IN JET ENGINES

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ABSTRACT

In aero-engines, titanium fire occurs in the fan and compressor where titanium is indispensable because of its high strength-to-weight ratio. Titanium alloys are mainly used for blading, casings and disks. Consequently, if bearing- or blade-failure occurs, the possibility of an uncontained titanium fire cannot be excluded.

A titanium fire is a very short event of about 4 to 20 seconds duration depending on the engine design and the operating conditions. It is a violent conflagration accompanied by temperatures as high as 3,300°C. This energy destroys surrounding materials, including steel and nickel alloys, by burning and melting. When this happens, the airframe structure can be severely damaged, even resulting in the loss of the aircraft. Extinguishing the fire is impossible because of its rapid propagation and the very short time between its detection after uncontainment and its termination. Common fire-extinguishing agents are not suitable for quenching a titanium fire because their composition is inadequate and sufficient quantity is not available. But these agents can prevent propagation of the fire in the engine bay.

The risk involved can be avoided by such measures as intelligent design, fire-preventive coatings, and use of titanium alloys that are not easily combustible. The development of preventive measures calls for rig tests in order to simulate burning conditions, and to verify the efficacy of the measures. Titanium can then be used safely in advanced-technology engines for modern aircraft.

1. INTRODUCTION: What is a titanium fire?

In a burning match one can see that a fire (here represented by the flame) generally is a process in which combustion takes place accompanied by the emission of light, heat, and usually also flames and smoke, as a result of reaction with oxygen; or as the chemist would put it, as a result of exothermic oxidation of a combustible medium (fuel).

That metals can also burn can be illustrated by two examples, namely a flash-bulb and a cutting torch:

- In the former, a fine magnesium or aluminium wire inside a gas-filled bulb is ignited via a filament and (as with the match) an oxidant. Combustion is supported by the oxygen atmosphere.
- In the latter example, when cutting steel plate, the surface of the workpiece is first heated by the oxy-acetylene flame, then the metal burns or melts away when the supply of acetylene is stopped and the flame is sustained by pure oxygen.

The combustion of a metal is not a diffusion reaction with oxygen at the surface of the metal, but is a heterogeneous reaction. In other words, solid, liquid, and gaseous phases are present, which hinders the process, meaning that metal and an oxidant must be transported to the site of combustion, for example by solid and liquid phases of both the metal and its oxides. Combustion occurs as a rapid, partially explosive process, and is influenced by the properties (eg thermal conductivity, ignition point, etc) of the metal, the size and shape of the object concerned (thin wire, sheet, or compact component), and the ambient conditions. Generally, the presence of oxygen, a bare metal surface, and the supply of heat, for example as a result of friction, are required for the ignition of a metal. The metals and their alloys which are among the most susceptible to ignition are titanium, zirconium, uranium, lead, tin, and magnesium.

We speak of a titanium fire in an aero-engine, which is the subject of this paper, when the "fuel" is a titanium alloy. The relative ignition temperature (eg 1,600°C in a standard atmosphere) is usually exceeded as a result of friction between the rotor and stator of the compressor. The high oxygen

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demand is met by the air as it flows through the engine, where there must be a certain correlation between the pressure, temperature, and flow velocity of the air. The fire will be sustained only for as long as the requisite amount of oxygen or "fuel" is present.

The consequences of a titanium fire which burns out of control, when temperatures in excess of 3,300°C [1] occur, can be severe blading damage, and burnthrough of inner casings in titanium and even nickel alloys. In extreme cases, burnthrough of the outer engine casing can result, and this is defined as an "uncontained titanium fire". If vital airframe structures and installations are affected, this can lead to the loss of the aircraft. Examples and the consequences of an uncontained titanium fire are shown in **figures 1 and 2**.

2. TITANIUM FIRE IN AERO-ENGINES

In 1954 when a titanium alloy was used for the first time in a jet engine (J77) [2], presumably nobody considered the possibility of titanium fire. But now that we are aware of the danger, why is the use of this material in aero-engines becoming more and more widespread? The answer lies in titanium's high strength-to-weight ratio.

2.1 CHARACTERISTICS OF TITANIUM

2.1.1 Mechanical properties

Titanium is a material that exhibits specific strength properties that are superior to those of steel or nickel alloys up to a temperature of 450°C. When protected with a thin oxide skin, it has better oxidation and corrosion properties than steel. However, the temperature resistance of most titanium alloys is poorer than that of steel and of the nickel alloys used in the hot section of engines, despite the fact that they have a melting point that is some 100 and 200 K higher respectively.

The outstanding advantage of titanium is its density of 4.5 g/cm^3, making it some 40 per cent lighter than steel (with a density of 7.8 g/cm^3) and about 50 per cent lighter than nickel (with a density of 8.9 g/cm^3). One result of this is that the use of titanium makes better thrust-to-weight ratios possible than could be achieved with other materials.

With regard to wear and notch sensitivity titanium is characterized by some disadvantages, but as far as the subject of this paper is concerned, they are of significance only in so far as primary blade damage could occur as a result.

2.1.2 Titanium alloys for service in aero-engines

Titanium alloys, such as Ti-6Al-4V, Ti-2Cu, Ti-6Al-2Sn-4Zr-2Mo, and Ti-6Al-4Sn-3Zr-1Nb-0.5Mo (IMI834), are used in modern aero-engines for fan and compressor (blading, rotor disks, casings), gearboxes, and the low-pressure turbine. Because of the restrictions concerning their creep strength and notch sensitivity, they are suitable for use only for peak temperatures of up to a maximum of between approximately 350 and 600°C.

The suitability of titanium for higher service temperatures also depends on its fire resistance, and severe restraints are placed on this aspect in view of the increasing economic demands for better thrust-to-weight ratios. These demands can be met only through
- lighter components with thin, reinforced walls,
- higher pressure ratios,
- higher component temperatures, and
- higher flow velocities.

2.1.3 Properties of titanium that can promote titanium fire

Properties of titanium and its alloys that can promote fire are
- the metal's ignitability, and
- its exothermic, partially explosive reaction with oxygen.

In addition, there is the
- risk of the fire spreading to downstream components in titanium as a result of the spin-off of molten, energy-rich droplets from rotating components.

These disadvantages are associated with the thermodynamic properties of titanium and its alloys (compared with Ni and Fe) [1, 3]:

- Low thermal conductivity (TC [W/mK]):
  $TC_{Ti} \sim 0.2\, TC_{Ni} \sim 0.3\, TC_{Fe}$

- High combustion energy (Q [J/mol]):
  $Q_{Ti} \sim 4.9\, Q_{Ni} \sim 2.3\, Q_{Fe}$

- High combustion temperature:
  $T_{Ti} \sim 3{,}300°C$

- Rapid reduction in ignition temperature with increase in oxygen pressure

- Ignition temperature (* in pure oxigen) [~°C]
  Ti: 1,330*/1,600 Ni: 1,330 Fe: 1,130/1,400
  < Melting temperature [~ °C]:
  Ti: 1,670 Ni: 1,450 Fe: 1,540

- Oxide is soluble in the molten metal
  Ti: yes Ni: no Fe: no

- Protective (dense) oxide layer
  Ti: up to 450°C Ni: yes Fe: no

- Titanium burns at the surface (evaporation temperature: oxide < metal).

2.1.4 Causes of ignition

Ignition of titanium can be caused by heat generated by axial or radial contact between rotating and stationary components. Typical conditions are:

- When an object such as
  - a blade fragment (primary damage), or
  - a flat foreign body in steel or nickel alloy

  becomes entrapped at the blade tip, resulting in rotational friction against the casing, which then provides a bare, oxide-free surface necessary for ignition (metal-to-metal contact);

- At casings or seals in case of:
  - bearing failure,
  - rotor unbalance, or
  - (rarely) high g-loading under certain flight manoeuvres.

- When rubbing between seals occurs (rarely) as a result of
  - chipped linings,
  - thermal expansion of labyrinths,
  - fatigue cracking of stationary member, or
  - when radial expansion of the stationary member is hindered.

Other rare causes can be
- high-velocity impingement of a sharp-edged object against a titanium surface (own/foreign object damage),
- aerodynamic heating as a consequence of stall,
- thermal radiation by a hot body or gas.

2.1.5 Conditions which are conducive to titanium fire

Such conditions in the engine are:

- Partial pressure of the oxygen
  - provides a sufficient amount of oxidant,
  - determines its absorption rate, and, therefore,
  - governs the reaction at the metal surface.

- Velocity of the airflow through the engine determines
  - the rate at which molten metal is dispersed, and thus
    - the transfer of heat, and
    - the combustion (rate and duration)
  - the size of the molten titanium droplets, and thus
    - the surface area available for the reaction with oxygen,
    - the amount of heat generated, and
    - the extent of the molten region.

- Pressure and velocity of the airflow are responsible for
  - blowing away the slag at the fire-front, ie giving access to oxygen to support combustion of the oxide-free surface of the titanium material (ie "fuel").

- Ratio of the component surface to its volume determines
  - the ignition time (and temperature),
  - the burning time, and
  - the extent of burning.

- Centrifugal forces, viscosity of the molten metal, and surface tension determine
  - the rate (and duration) of burning, depending on the adhesion of the molten metal.

- Ambient temperature determines
  - the difference between the temperature of the molten region and that of the adjacent metal, and thus
    - the temperature gradient, and
    - the rate of dispersion of the molten metal.

- Additional supply of energy (primary damage) causes
  - rapid ignition.

2.1.6 Conditions which hinder ignition or extinguish titanium fire

Conditions in the engine that hinder ignition or result in fire being extinguished are:

- Source of ignition is removed in time
  - when the radial or axial gap is widened in good time when rubbing occurs, ie before the ignition point of an adjacent or downstream titanium component is reached.

- The oxygen pressure, temperature, and flow velocity are not/are no longer critical
  - Titanium fire does not occur if the relative ignition temperature is not reached as a result of
    - the operating conditions under part load, and
    - thicker wall cross-sections (heat is dissipated).

- The fire will die out locally or completely when
  - there is no longer sufficient oxygen available

at the fire front, as can occur
  - under deceleration or
  - because the slag is not fully blown away,
- the fire front reaches a colder surface, or
- a thicker titanium cross-section,
- the heat is dissipated by a (massive and) conductive component, or
- the fire front reaches a non-combustible (or not easily combustible) obstacle (eg vane platform in a nickel alloy).

- There is no longer any titanium left:
  - The fire will then go out. But this happens only with smaller or thinner titanium blade fragments and provided that the fire has not spread to other areas.

2.1.7 Limits concerning ignition and sustainment of a titanium fire

The following limits are cited in the literature [1]:

- CAA criterion — Engine maker's approx. values

CAA criterion	Engine maker's approx. values	
$p > 2$ bar	$p = 1$ bar	$p = 3$ bar
$v > 50$ m/s	$v \sim 120$ m/s	$v \sim 45$ m/s

- Heating rate <--> ignition temperature:

40 K/s	<-->	<1600°C
100 K/s	<-->	300 to 400°C

- Volume-related surface (A/V [cm^2/cm^3]) with massive components:
  Bulk behaviour < 25.6 cm^{-1} --> ignition temperature ~1,330°C at 1 bar in oxygen atmosphere

- $v > 183$ m/s --> immediate ignition
  $v > 275$ m/s --> fire is extinguished as result of dissipation of the molten metal accompanied by cooling

- Ignition (without airflow) at
  $T_{ambient}$ and 25 bar, or
  500 °C and 7 bar.

2.2 STAGES AND EFFECTS OF TITANIUM FIRE IN (MILITARY) ENGINES

2.2.1 Preliminary stage

The preliminary stage of a titanium fire can be seen at the tips of titanium rotor blades if they rub against the inside of the casing. The material abraded from the blade tips and casing wall builds up on the blade tip, forming a wedge-shaped deposit with only very slight, local melting (**figure 3**). The first sign of a fire occurs with greater loss of material from the blade tips accompanied by the formation of a black crust at the pressure side of the blade close to the tip (**figure 4**), and frequently also on the adjacent guide vanes. These crusts can be removed only by grinding.

Loss of material and the formation of a crust also occur at the point of impact (**figure 5**) as the result of high-energy collision against a titanium component by a fragment of a blade or a foreign body, for example in a nickel or iron material.

2.2.2 Titanium fire in compressor

A local fire occurs when a fragment of a titanium blade impinges against a thin-walled section of a titanium casing. Certainly, the energy of impact is such that the fragment will normally be burnt up (**figure 6**), but burnthrough of the casing wall is also possible (**figure 7**). A crust forms around the site of the fire, and temper-colouring occurs at the outside of the casing.

Rotor blades in titanium usually burn only at the tips and thin edges (**figure 8**), since the fire dies out quickly as a result of centrifugal force with burning material being spun off and the thermal energy thus being dissipated.

Localized or widespread burnthrough of a titanium casing and thus a larger fire in the compressor and other components (**figure 9a**) are possible if high frictional heat occurs at the casing wall. As pointed out earlier, a flat nickel or iron object, for example, can become lodged at a blade tip in any material, and thus rotate with the blade and so cause the casing to ignite.

In addition to the burn marks, thin engine components in titanium damaged by fire exhibit typical changes, such as

- temper colouring (similar to Newton rings, **figure 10**), occurring after "low" heat-absorption on walls with lateral transition to thicker cross section,
- flat micro material displacement (**figure 11**),
- oxidation of the surface (light-grey deposit, **figure 11, 12**), occurring shortly before burnthrough,
- localized intercrystalline cracking in casing rings (**figure 12**).

Naturally, the molten products (**figure 9b**) can also penetrate walls in materials other than titanium, giving rise to either local overheating or in extreme cases even burnthrough, depending on the thickness of the wall and properties of the material. Although the recast layer often flakes off when the engine has cooled, the overheating damage remains.

2.2.3 Uncontained titanium fire

A titanium fire of such proportions that the outer casing of the engine is penetrated is defined as uncontained. At high rotational speed, this will take a mere 10 to 15 seconds, depending on the casing material, the wall thickness, and the number of "shells". The axial and radial extent of such an uncontained titanium fire as a consequence of bearing failure is illustrated schematically in **figure 13.**

2.2.4 Effects of fire on other components

Extensive compressor-blade damage can have serious aerodynamic consequences. Lock-in surge occurs, and the control unit tries to compensate for loss of spool speed by the addition of fuel. Up to the maximum flow of fuel is injected, and the igniter plugs are reactivated. The engine tries to increase speed until it succeeds or until the fuel supply is shut off manually by the pilot again. The burning of this additional fuel increases the turbine entry temperature, contributing to premature damage to the turbine blading (**figure 14**). Furthermore, the compressor air for cooling the turbine is heated by the fire and contains combustion products, meaning that cooling is lost as the spool speed (and air velocity) decreases.

The consequences are more and more extensive burning and breakage of the turbine rotor blades, made worse as a result of centrifugal force. Extensive burning of the stator can occur, finally leading to serious weakening of the engine structure (mounts, bearing systems, etc).

If the titanium fire results in fuel lines being burnt through (**figure 9a**), a fuel-fire can occur in the bypass, but normally without serious consequences unless the ignition or melting point of the surrounding walls is reached.

The main danger of an uncontained fire is the loss of major pipelines, electrical cables, actuating levers and motors, engine-bay installations, and even airframe damage. As remote worst-case consequence, this can lead to loss of the aircraft (**figure 2**).

2.2.5 Recognition of a fire, corrective action

Because of lack of suitable instrumentation and the speed of events, the possibilities for the pilot to recognize a titanium fire and take appropriate action in flight are severely restricted. Usually, the resulting mechanical damage will trigger a vibration warning. Blade destruction (as a result of primary damage) and the fire cause lock-in surge, and an increase in exhaust temperature will be indicated. But this is typical with lock-in surge, for example, even at sub-idle, at low flying speeds at high altitudes, and with control-unit malfunctions. The pilot will only receive an engine-bay fire warning after the damage has become extreme, ie after the outer casing has been burnt through.

If he suspects a titanium fire, that is to say in cases of doubt about the cause whenever lock-in surge occurs, the pilot should shut the engine down immediately by closing all fuel valves, and so prevent the automatic adjustment of the fuel supply in an attempt to stabilize the engine speed.

The engine is not provided with fire-fighting systems. Moreover in view of the short duration of a fire (15 to 20 seconds max), extinguishing the fire would be pointless as far as the engine is concerned, since a limited once-only action by the airframe extinguisher system can be taken to prevent the fire from spreading any further only after it has reached the engine bay. The fuel supply to the engine concerned must be shut off beforehand.

It is possible that there is no compatible extinguishant for combating titanium fire. The agent Halon 1211, currently provided in the engine bay, is a CF_2ClBr solution which is effective but toxic and corrosive, since at a temperature of 450°C and above it becomes instable, decomposing into HBr-HF-HCl, and at higher temperatures even these molecules will dissociate. CO_2 is similarly unsuitable and would even support the burning of titanium, since oxygen has a greater affinity for titanium than for carbon. A conceivable alternative agent would be air containing 60 per cent argon or helium. But a high volume of noble gas would be required.

2.2.6 Disposal of damaged components (inspection, assessment)

Engine components with visible damage are generally unserviceable and are to be scrapped. With a titanium fire that has been confined to a limited area, components that have been affected by molten droplets or hot air must be inspected for surface damage. Rotor disks will normally be serviceable, but if the air used for cooling has been heated by the fire, the disks will have to be thoroughly examined.

3. PREVENTION OF (UNCONTAINED) TITANIUM FIRE

3.1 DESIGN MEASURES

In order to minimize the risk of titanium fire it is necessary to preclude the possibility of primary damage as far as possible, for example by

- avoiding direct frictional contact between rotor and stator components in titanium (by providing an anti-wear spray or ceramic coating, and the use of steel or nickel alloy for the stationary components);

- avoiding thin casing walls (ie of weakened cross sections) in areas in which rubbing by rotor-blade tips occurs;

- avoiding very thin leading edges on rotor blades and guide vanes (notch sensitivity of titanium alloys is a cause of primary failure);

- making sure of adequate bearing safety or carrying out chip-detector inspection to avoid bearing failure with subsequent rubbing between titanium components;

- making sure of adequate casing rigidity in order to restrict thrust- or pressure-related axial movement;

- maintaining clearances to avoid thermally- or operating condition-related (hot reslam, surge, etc) relative movements between the rotor and stator, which can be a cause of rubbing;

- making sure that the axial clearance between rotor and stator is narrowest at the point where the maximum component temperature is lowest;

- providing axial contact surfaces in a material with good insulation properties and high temperature resistance to allow safe rotor braking in the event of bearing failure;

- considering the use of vanes fitted with inner shrouds rather than cantilevered design;

- considering the use of brush seals instead of labyrinth seals.

3.2 AVOIDENCE OF CAUSATIVE DAMAGE

The best protection against titanium fire is to try to avoid damage that could result in titanium fire, and to achieve this a statistical study of the damage and its causes, based on different types of engine if appropriate, is recommended. If the damage recurs, corrective action, including the above design measures, must be taken as soon as possible. At the very latest, action must be taken immediately following a case of titanium fire. The pilot can play his part by making sure he observes the engine manufacturer's recommendations, and if possible by recording essential data when a fire occurs.

3.3 PROTECTION AGAINST TITANIUM FIRE

In a jet engine, primary damage accompanied by secondary damage in the form of serious rubbing or the impingement of a metallic body cannot be totally excluded. Consequently, to avoid uncontained titanium fire as far as possible, endangered titanium components must be provided with protective coatings that will at least prevent burn-through in the most active, initial phase of the fire (at full-load operation).

Alternatively, new engines can be fitted with suitable new titanium alloys, or old ones can be correspondingly modified. For hotter areas, the use of materials with high aluminium content, which will reduce the risk of fire, is recommended. Alloys with a higher chromium or vanadium content (such as alloy type "C" [4]) are suitable for lower-temperature areas. However, these materials are still under development.

3.3.1 Coating properties

Coatings for protection against uncontained titanium fire need to have the following main characteristics:

- capability to prevent direct frictional contact between titanium rotors and stators to ensure ignition cannot easily occur;

- capability to give protection at least during the most active, initial phase (maximum aero-dynamic conditions) of the fire;

- good mechanical properties, such as durability, and stability under normal maximum conditions (where the latter also calls for adequate stability of the parent casing).

In addition, a number of secondary properties are required, that is to say
- high resistance to oxidation,
- high resistance to temperature changes,
- high resistance to corrosion (incl under mechanical loads),
- high resistance to erosion (when applied in the main air-flow passage), and
- good adhesion.

3.3.2 Theoretical considerations in selecting a coating

Mechanisms involved in the function of coatings

Advantage can be taken of a number of physical and chemical material properties for protecting against titanium fire. For example, there are ablat-

ive coatings, which melt or evaporate rapidly as a result of their low transformation points. The resulting thermal energy can be dissipated via the airflow through the engine, meaning that the heat is largely kept away from titanium walls. Then there are coatings with very high melting points and low thermal conductivity, where despite residence time on their surface, molten titanium will not do any major harm (**figure 15**).

Other parameters are viscosity of the molten metal, surface tension, and wettability of the surface. By careful coating design, the wetting by the molten metal and the residence time on the surface can be minimized.

The inclusion of other alloy elements which reduce the solubility of oxides in molten titanium and promote the formation of an oxide skin on the surface also helps reduce the risk of fire.

As an additional measure, elements with maximum activation energy for oxidation can be included in the coating (eg Ni, Cu).

Analytical and empirical models

These models [1] are used for comparing the energy released by chemical reaction with that lost by
- thermal conductivity,
- convection,
- radiation, and
- molten metal carried away in the airflow.

The most common variables used are
- aerodynamic temperature, pressure, and velocity at the site of the fire,
- Reynolds number at cross sections of titanium components downstream of the airflow,
- physical values,
- diffusion of oxygen, and
- geometrical values.

However, because of uncertainties about energy from external sources, these models are not very reliable, and can thus be used only to a limited extent for making predictions.

4. RIG TESTS

Rig tests are one method for verifying the effectiveness of protective coatings or new titanium alloys before these coatings or alloys are used in the engine, where it must be possible to

- simulate the effects of a titanium fire in the engine, and

- check the suitability and effectiveness of coatings applied to substrates that are used in the engine, and to determine the minimum coating thickness required.

4.1 LAYOUT OF TEST RIG

The main components of the rig (**figure 16**) are

- test chamber (thick-walled steel tube with good thermal-transport characteristics),

- compressed-air connection (supply from cylinders or plant system),

- air preheater (electrically-heated high-capacity system as heat exchanger),

- adjustable specimen carrier to allow simulation of various impingement angles of the hot flash (including thermocouple for monitoring the temperature of the specimen),

- titanium strip of defined mass, which is ignited in order to simulate the effects and duration of the fire,

- igniter (electrical or other, eg laser),

- exhaust diffuser with adjustable outlet,

- instrumentation for measurement of temperature, pressure, and airflow velocity,

- TV camera to allow the processes inside the test chamber to be observed and recorded (size of the molten droplets in the airflow, reactions taking place at the specimen surface, interaction with the airflow, and duration of the fire).

Note:
- The distance between the specimen and the burning titanium strip, the combustible mass of the strip, and the impingement area depend on the conditions in the engine, as do the
- air pressure, velocity of the airflow at the end of the acceleration path, and the temperature of the preheated coating carrier before ignition of the titanium strip.

4.2 RIG-TEST CAPABILITIES

Difficulties in the testing of protective coatings:

- Reproducibility of the tests is an absolute must, ie all test parameters must be precisely adhered to, and unwanted reactions (eg with rig components) must be avoided.

- A statistical record is required in order to verify

each result; and for this, more than 20 tests per coating under nominally identical conditions is recommended.

- The data concerning the combustibility of metals are relative and not absolute, because they depend on the test conditions and the nature of the test. Hence comparability of the results with those according to the literature is usually not possible.

It should be noted that no matter how carefully the rig test is planned and carried out, it can only be a substitute for running in the engine itself. The correctness of the concept and the mechanical stability of a coating can be verified only under normal operating conditions over the course of time in the engine. Only service experience will reveal any difficulties arising from the implementation of the measure tested or highlight any previously disregarded or unforeseeable variables (eg durability of the coating under multiple loads, natural stresses in the casing, changes of aerodynamic or thermodynamic, different damage characteristics of the coating) that might change the engine behaviour.

5. CONCLUSION

In spite of the problems and the possible extreme consequences of a titanium fire, mentioned above, no-one should be deterred from ever boarding an aircraft again. Because of the relative simplicity of the flight, the rate of damage in commercial aviation is appreciably less than that with military aircraft, where the flight is characterized by constant load changes affecting numerous components. The crash rate because of titanium fire is very low, since only a fraction of the total potential primary damage results in titanium fire, and not every fire will be uncontained. Moreover, not every uncontained fire will end in the loss of the aircraft. This is attributable to the fact that all engine makers have long been aware of the danger, and are constantly introducing both design and computational improvements in order to combat the problem.

6. ACKNOWLEDGEMENT

The authors wish to thank MTU München for permission to publish this paper, and to express their gratitude to their colleagues for their assistance and cooperation.

7. REFERENCES

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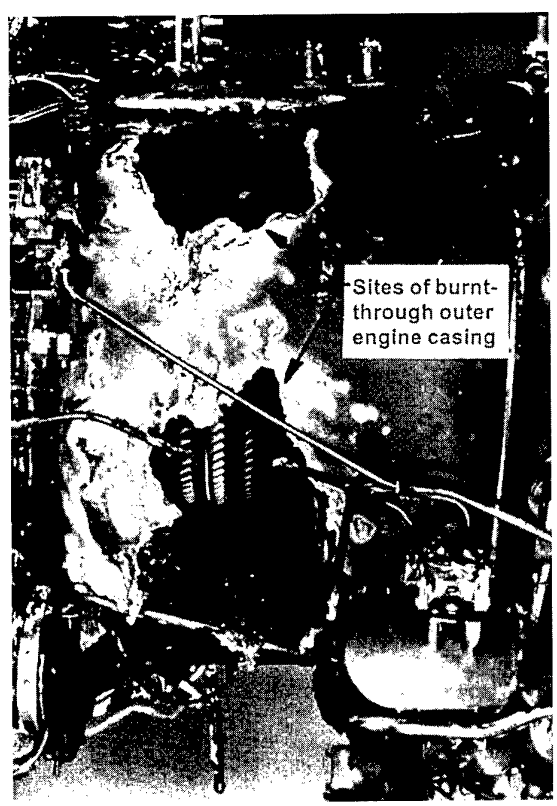

Fig. 1:

Uncontained titanium fire; the outer casing of the engine has been penetrated

Fig. 2:

Engine after aircraft crash (with uncontained titanium fire having contributed to the crash)

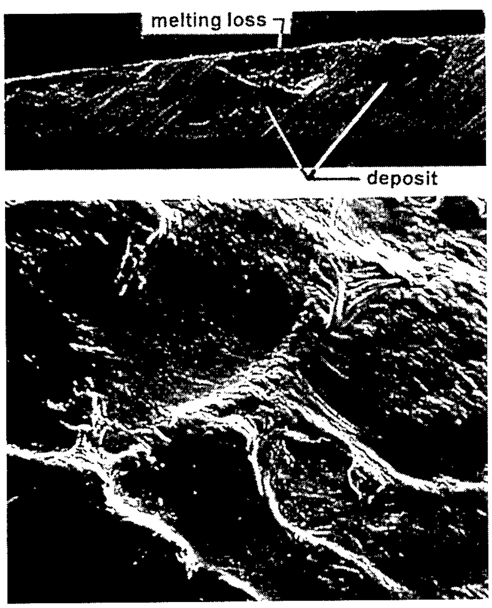

Fig. 3: Prestate of titanium fire on a blade tip;
a) Deposit (Ti-Ni material)/local melting losses
b) Typical view of the molten area (enlarged)

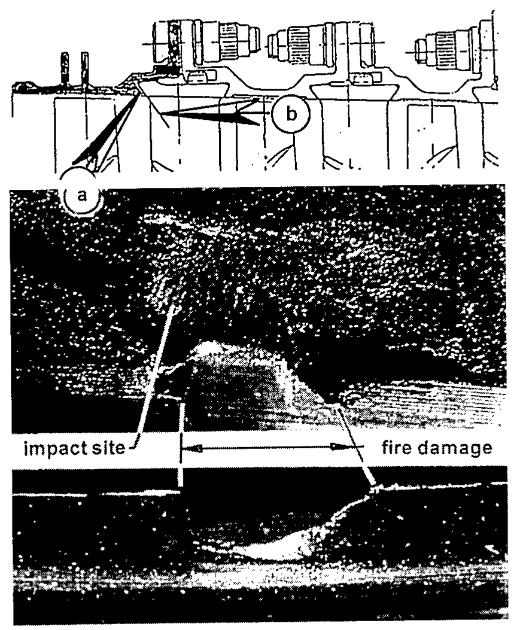

Fig. 5: Local titanium fire following hard-body impact;
a) Impact site on casing wall, and fire damage
b) Fire damage on thin casing wall

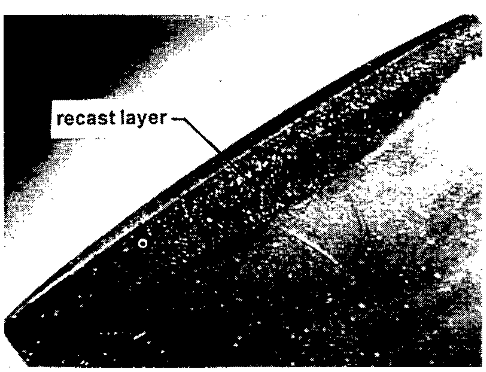

Fig. 4: Rotor blade, concave side, showing black Ti-Ni recast layer resulting from (mini) titanium fire

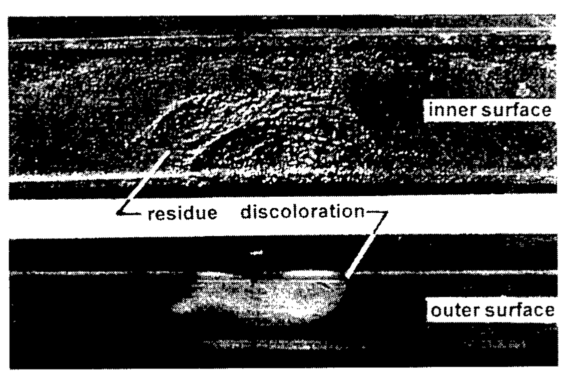

Fig. 6: Residue of a flat fragment from a titanium blade adhering to the compressor casing after ignition/fire;

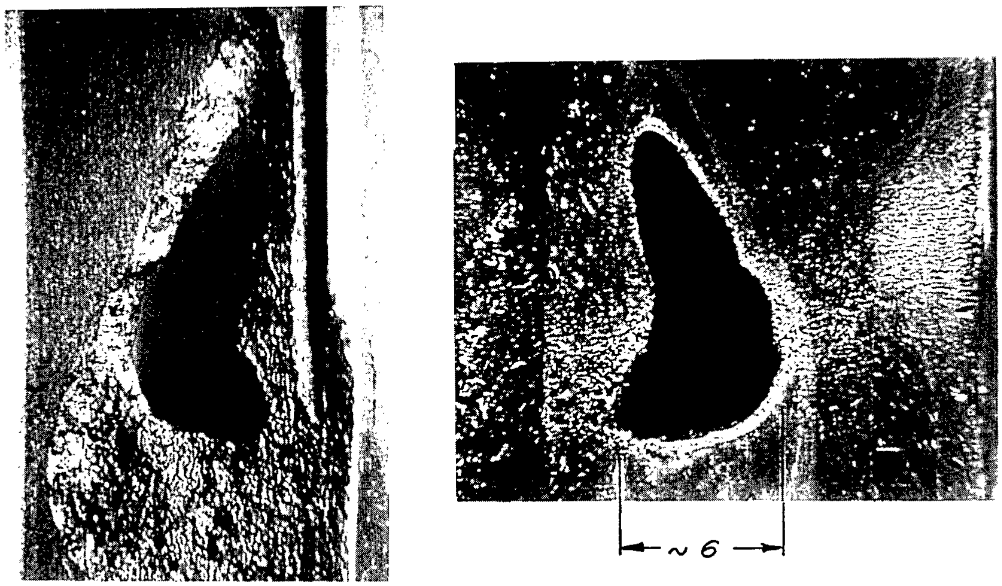

Fig. 7: Compressor casing penetrated by a local titanium fire as result of entrapment of a blade fragment followed by rubbing against the casing;
a) Inner surface of the casing (cleaned condition)
b) Outer surface of the casing (with titanium spatter)

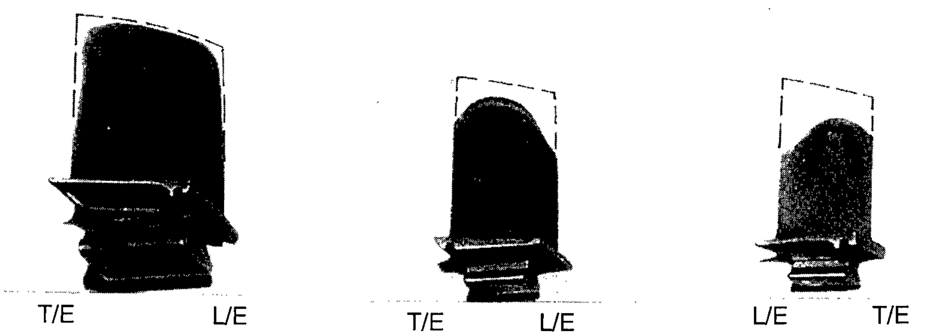

Fig. 8: Fire damage at blade tips

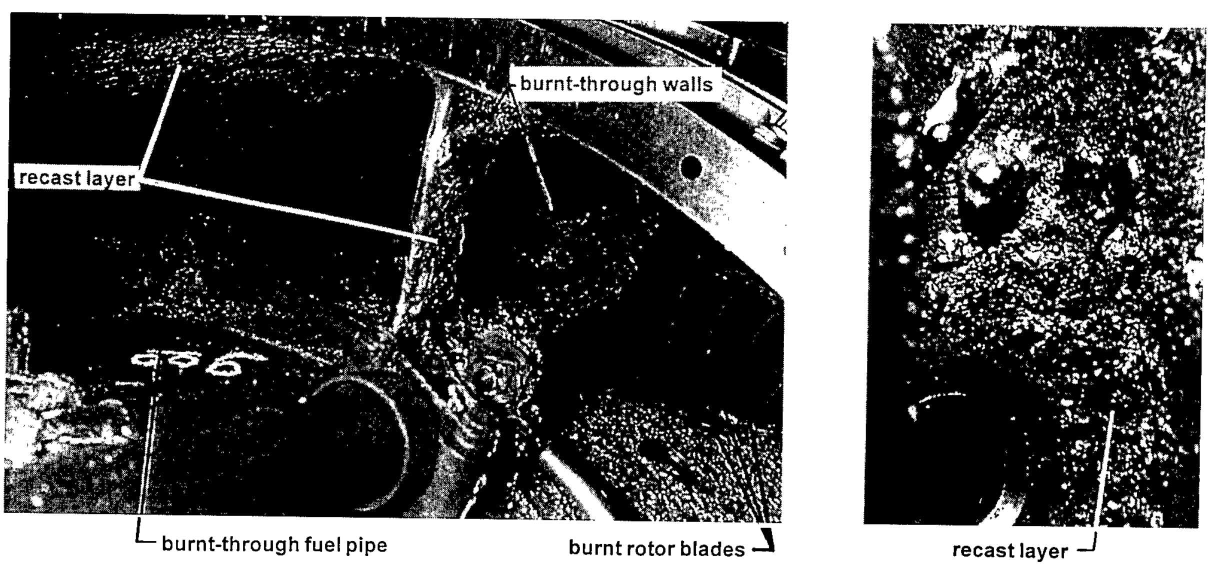

Fig. 9: Typical titanium fire with formation of a recast layer on the casing surface;
a) General view of burnt rotor blades and burnt-through casing wall with recast layer
b) Enlarged view of the recast layer

Fig. 10:

Typical sequence of 'Newton rings' on thin titanium walls, indicating incipient overheating as a result of titanium fire or contact with molten products

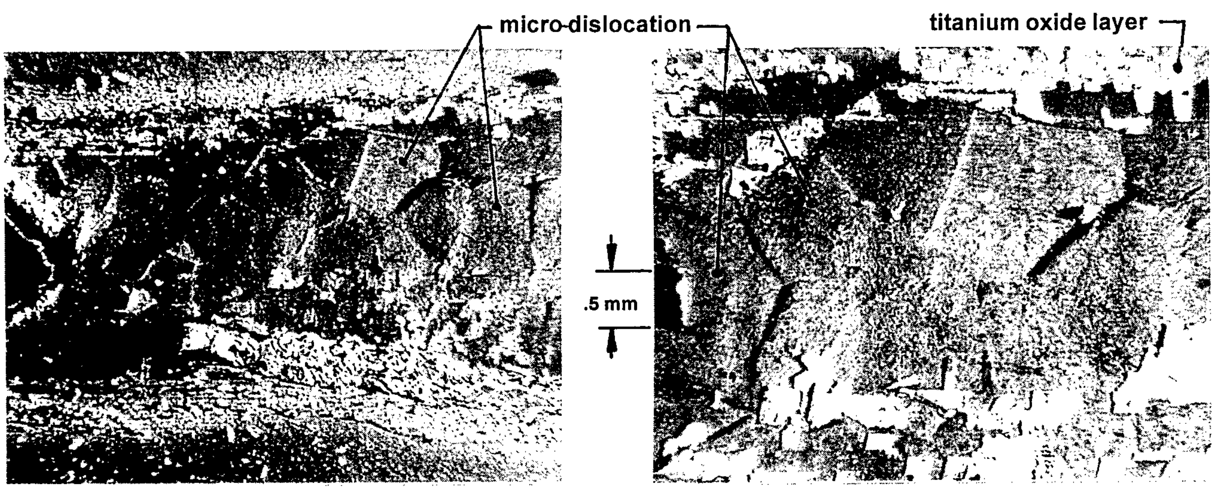

Fig. 11: Typical surface of a thin titanium wall prior to melting/burn-through: Formation of surface oxides and micro-dislocation of grains
a) Area close to burnt-through section (left-hand side) with micro-dislocation (surface oxides partly removed)
b) Enlarged view

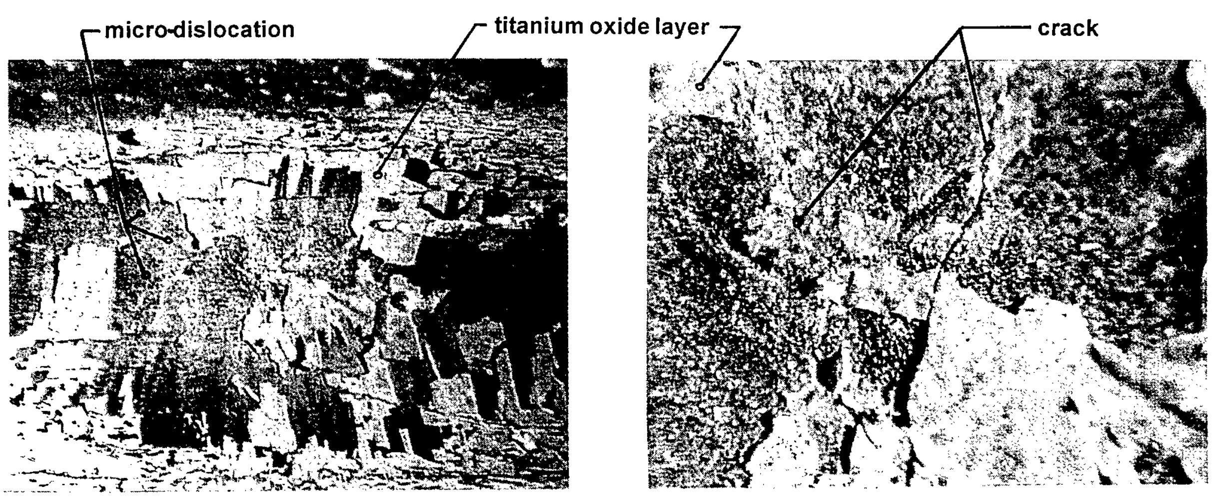

Fig. 12: Formation of cracks prior to melting/burn-through of a thin titanium wall;
a) Environment of cracked area with micro-dislocation and formation of surface oxides
b) Enlarged view of the cracked wall (surface oxides partly removed)

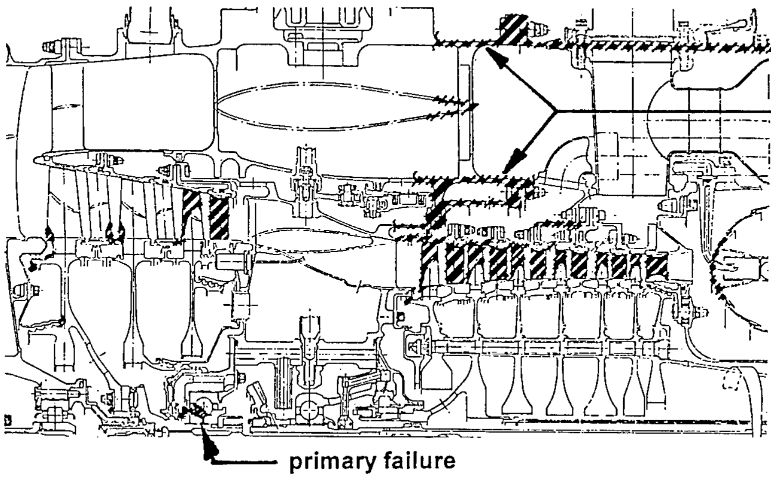

Fig. 13:

Radial and axial extent of titanium fire in a military engine (schematic)

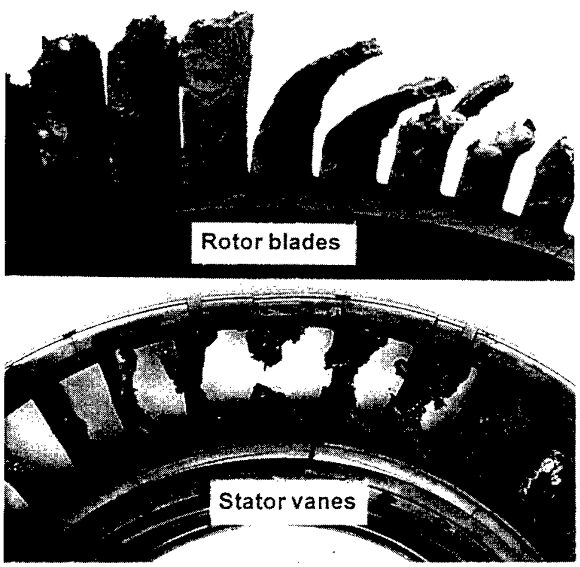

Fig. 14: Damage to turbine blading following over-fuelling subsequent to titanium fire

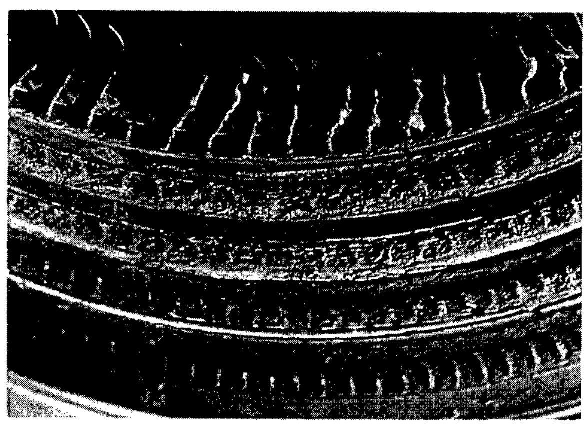

Fig. 15: Titanium fire in a compressor where casing walls are protected with a ceramic coating

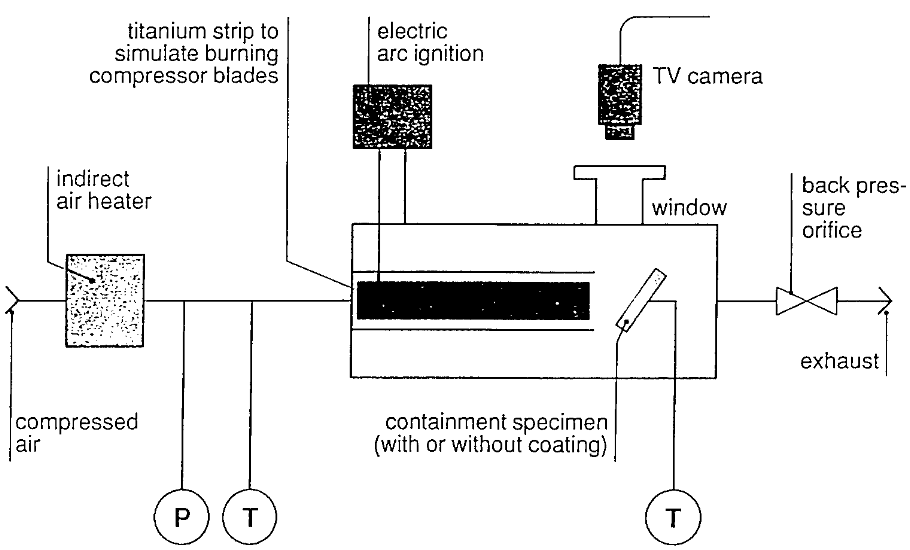

Fig. 16:

Schematic showing an experimental set-up for simulation of titanium fire, and testing of protective coatings

GLARE®; a structural material for fire resistant aircraft fuselages

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1. SUMMARY

GLARE® consists of thin aluminum alloy sheet and fiber layers containing strong unidirectional glass fibers and epoxy adhesive. The material has been optimized to overcome the corrosion and fatigue problems of monolithic aluminum alloys and meets all requirements for use in primary aircraft structures.

In 1994 several GLARE® grades with biaxial fiber layers were certified to the fire resistance requirements for cargo liners specified in FAR 25.855. The material even resists an 1100°C flame for more than 15 minutes without penetration.

The fire resistance of GLARE® together with the materials' outstanding impact properties makes GLARE® an attractive candidate for future application in cargo liners and floors. The behaviour of GLARE® in blast-resistant containers providing fire resistance after the blast, proves the materials' capabilities. Due to its material properties GLARE® is also attractive for fuselage skin applications. This is one of the few options to have fire resistant fuselages in the near future.

2. INTRODUCTION

The Fiber Metal Laminate GLARE® consists of 0.2 mm to 0.5 mm thick aluminum alloy sheet bonded together with epoxy adhesive layers containing 60 volume percent of high strength glass fibers. GLARE® has been developed as fuselage skin material providing superior fatigue behaviour and damage tolerance over conventional aluminum alloys. After introduction of this material in 1990, the material showed to provide fire resistance characteristics in tests by several aircraft manufacturers. In addition to this unexpected feature the material also showed improved impact resistance over monolithic aluminum. These two aspects, together with the general material behaviour, made GLARE® an attractive candidate for applications requiring fire resistance. Today the material is considered in several areas traditionally using composite type firewalls. However GLARE® is also under consideration as fuselage skin material. It has abilities to protect the passengers from an outside fire; an event for which proper protection systems do not exist today.

This paper presents GLARE® as a firewall material for cargo areas and as a structural material for fuselage skins combining safe behaviour from corrosion and fatigue point of view with fire resistance.

3. GENERAL MATERIAL BEHAVIOUR

The composition of GLARE® laminates is shown in table 1. The mechanical properties of these materials in comparison with aluminum alloy 2024-T3 are indicated in table 2.

A crack bridging effect is provided by intact fiber layers in case fatigue cracks occur in the metal sheets of the laminate. The load transfer from metal layers to fiber layers in the wake of the crack in the aluminum layers causes some delamination between metal layers and fiber layers (figure 1). The crack closing stress in the fiber layers reduces the stress intensity factor at the crack tip in the metal sheets of the material, reducing the fatigue crack growth rates in the material (figure 2). The size and shape of the delamination area influences the crack growth behaviour and depends on the laminate ingredients, volume fractions and layer thicknesses for the various grades of GLARE®. For monolithic aluminum joints, crack initiation results in fast crack growth through the thickness of the material until failure of the joint occurs. Detection of the fatigue damage before failure occurs, requires frequent inspection. In GLARE® joints the fatigue damage stays in one layer for a large number of cycles before a crack in the next layer initiates and a fatigue crack starts growing (figure 3). Failure of the GLARE® joint occurs generally only after all metal sheets are fully cracked. The advantage of this behaviour is that even with longer inspection periods than for aluminum joints a much safer structure is obtained (figure 4).

The corrosion behaviour of GLARE® can be deduced from the properties of its constituents, aluminum alloy and glass fiber composite. The metal sheets behave similar to conventional aluminum sheet (one of the standard options for GLARE® is the use of -single side- clad aluminum layer on the outside of the laminate to reduce surface corrosion). As soon as the corrosion damage has reached the outer glass composite layer, further corrosion growth in thickness direction is prevented (figure 5). The surface

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corrosion behaviour of GLARE® is therefore better compared to monolithic aluminum alloy. Tests have shown that the combination of corrosion attack and fatigue load conditions (one of the biggest concerns for aircraft structural integrity) gives a much better behaviour for ARALL® than for aluminum 2024-T3 (figure 6) (ARALL® is a material similar to GLARE® but has aramid fibers instead of glass fibers).

After corrosion and fatigue damage the occurrence of impact is the next important cause for repair in aircraft structures. The high strength glass fibers provide superior impact properties for the GLARE® grades with equal amount of fibers in L and LT direction, GLARE® 3 and GLARE® 5. This aspect resulted already in two applications for GLARE® 3 (Boeing 777 bulk cargo floor and Shorts Lear 45 forward bulkhead).

Other advantages of GLARE® over conventional materials are:

* low weight
* excellent lightning strike capabilities
* thermal insulation
* easy reparability
* traditional workshop properties and
* FIRE RESISTANCE.

4. FIRE RESISTANCE

The use of the fire resistance of GLARE® laminates can be separated in at least four areas:

* firewalls and floors in cargo areas
* cargo containers
* fuselage skin
* engine plating, APU, electronic equipment boxes.

The last item will not be addressed here.

● Firewalls and floors

The fire resistance of GLARE® for application in firewalls and floors has been confirmed by several aircraft manufacturers. The material typically shows no burn through or flame leakage after 15 minutes exposure to a 1100°C oil burner flame. In 1994 several GLARE® grades with biaxial fiber layers were certified to FAR 25.855 (figure 7). The materials meet the burn through requirements for cargo liner materials. The burn through protection of the material is provided by the unidirectional cross-ply glass fiber layers. Fire tests have shown that the outside metal sheet of a GLARE® laminate melts away in only seconds. After that the adjacent glass fiber/epoxy layer delaminates from the remainder of the material over the exposed surface. The epoxy resin burns away in a maximum of 30 seconds leaving the cross-ply S-glass fibers covering the remainder of the laminate. At the same time delamination in the laminate has occurred providing further insulation of the intact layers of the laminate from the fire. This stable configuration does not change in the rest of the test. Figure 8 shows the exposed and unexposed surface of the laminate after 15 minutes of testing. The temperature of the aluminum sheet at the "cold" side of the specimen does not exceed 300°C.

The thinnest GLARE® grade meeting the cargo liner requirements has a thickness of 0.65 mm and an areal weight of 1.60 Kg/m^2. Evaluation of the properties which are important for firewall liners, has indicated the significance of the impact behaviour. Standard composite type firewall liners have shown poor impact behaviour. Comparison tests on small samples have shown that the puncture resistance of the thinnest fire resistant GLARE® material (GLARE® 3-2/1-0.2) is more than 3 times higher than the puncture resistance of a typical 1 mm thick glass/phenolic firewall material. Additional advantages of GLARE® firewalls over conventional firewall materials are:

* a relatively high bearing strength provided mainly by the metal sheets in the GLARE® laminate
* good abrasion resistance
* low areal weight
* easy formability
* simple manufacturing techniques (shearing, drilling)
* low moisture absorption due to the outside metal sheets
* high peel strength as a result of the use of epoxy adhesive.

Floor and ceiling of the cargo area are made of aluminum or composite material today. In case of aluminum, the structure is not fire resistant and needs additional protection to obtain this capability. The composite structure can be fire resistant, however it will need frequent repairs and often replacement because of impact damage. The, for impact protection, optimized GLARE® 5 grade solves the problems of conventional materials. It is fire resistant and has impact properties significantly better than composite materials and even monolithic aluminum (figure 9). A GLARE® 3 floor installed in an impact critical area of the Boeing 737 bulk cargo floor has already shown a considerable improvement over monolithic aluminum. It did not contain critical damage after more than 2.5 years of flight evaluation (figure 11) whereas the classical aluminum floor used at that location needs replacement at least once a year.

- Cargo containers

For many aircraft the superior impact resistance of GLARE® used as floor material or firewall is not required because luggage is stored in containers which are transported in the cargo area by a dedicated system. However the cargo container itself may become a product which will need the benefits of GLARE® on impact and fire resistance as a result of changing requirements for this product. One of the advantages of the glass fibers used in GLARE® is the increasing strength and strain to failure at increasing strain rate (figure 11). This effect results in further increase of the impact strength of GLARE® for these high strain rates. Studies on blast-resistant cargo containers have resulted in the evaluation of GLARE® 5 using the high strain rate effect. The first tests by Galaxy Scientific have shown that the material is capable of restraining the blast considered in these studies (figure 12). Even more surprising was the observation that the material contained the fire which occurred in the container after the explosion. So, the test has shown the advantage of the combination of impact resistance and fire resistance in one material.

- Fuselage skin

Fuselage skins are manufactured from aluminum; a material without any fire resistance. This is clearly observed from recent accidents as the Garuda DC10 (figure 13) and Belgium Airforce C-130 (figure 14).

The composite fuselage structure used today for some small aircraft seems to allow for fire resistant capabilities if adjustments are made. However a breakthrough for large composite pressurized fuselages does not seem realistic within the next decades. Conventional liner protection of the passengers by a composite type firewall located at the inside of the skin does not seem to improve the fire resistance of the structure significantly. The liner (attached to the aluminum skin structure) will not remain geometrically stable as soon as the aluminum skin, stringers and frames are melted away.

The best option to obtain a fire resistant fuselage seems to be the use of a fire resistant skin. Only in that case the stringers and frames can remain intact, supporting the skin material which should protect the inside of the fuselage from the outside fire. At this moment GLARE® is the only structural material having built-in fire resistance capabilities and is also able to carry all structural loads during the normal operational use of the aircraft. It is believed that GLARE® used as fuselage skin material improves the fire resistance of the structure. For aircraft accidents where the fuselage structure remains intact after the event, the fire resistance of GLARE® provides a significantly better protection of the passengers from an outside fire than any other fuselage material.

Obviously, only when specifications on the fire resistance of fuselage structures have become available, the suitability of GLARE® to meet these requirements can be verified. On the other hand these specifications will be compiled only when solutions are believed to be available. The GLARE® grades with biaxial glass fiber layers represent this first difficult step towards the development of fire resistant fuselages. It is time that the remainder of the development path of fire resistant fuselage structures is explored.

5. CONCLUSIONS

GLARE® with biaxial fiber layers (GLARE® 3, 4 and 5) meets the burn through requirements of cargo liners specified in FAR 25.588. Its superior impact behaviour over existing composites and aluminum alloys and simple workshop properties makes GLARE® an attractive material for floors, ceilings and liners in cargo areas of aircraft. The material has shown blast-resistant capabilities and subsequently fire containment. GLARE® is the only material presently available which can provide fire resistant aircraft fuselages. The material has shown to combine fire resistance with significant advantages over conventional aluminum alloys like superior fatigue behaviour, corrosion resistance and damage tolerance.

Table 1: material composition

material grade	metal		fiber layer	
	alloy type	thickness [mm]	orientaion	thickness [mm]
GLARE 1	7475-T761	0.3-0.4	0/0	0.250
GLARE 2	2024-T3	0.2-0.5	0/0	0.250
GLARE 3	2024-T3	0.2-0.5	0/90	0.250
GLARE 4	2024-T3	0.2-0.5	0/90/0	0.375
GLARE 5	2024-T3	0.2-0.5	0/90/90/0	0.500

Table 2: Mechanical properties (typical values).

		GLARE (1)					aluminum
		1	2	3	4	5	2024-T3
Tensile ultimate	L	1282	1074	717	930	682	455
strength [MPa]	LT	352	317	700	592	673	448
Tensile yield	L	545	360	305	352	296	359
strength [MPa]	LT	338	228	283	255	280	324
Tensile modulus	L	64	65	58	57	59	72
[GPa]	LT	49	50	58	50	59	72
Ultimate strain	L	4.1	4.5	4.5	4.5	4.5	19
[%]	LT	7.7	10.8	4.5	4.5	4.5	19
Compression yield	L		415	310	365		303
strength [MPa]	LT		236	310	285		345
Compression	L		67	59	60	59	74
modulus [GPa]	LT		52	59	54	59	74
Bearing ult. strength	L	834	727	819	662		945
e/D=2 [MPa]	LT		757	819			945
Blunt notch	L	793	765	496	593		414
strength [MPa] (2)	LT	352	283	496	414		414
Density [g/ccm]		2.49	2.48	2.48	2.40	2.50	2.77

(1) GLARE 1 to 4: 3/2 lay-up with 0.3 mm aluminum
GLARE 5: 2/1 lay-up with 0.5 mm aluminum
(3/2 lay-up: 3 layers aluminum, 2 layers fibers)
(2) specimen width = 25 mm, hole diameter = 5 mm

Figure 1: Fatigue crack bridging mechanism in GLARE

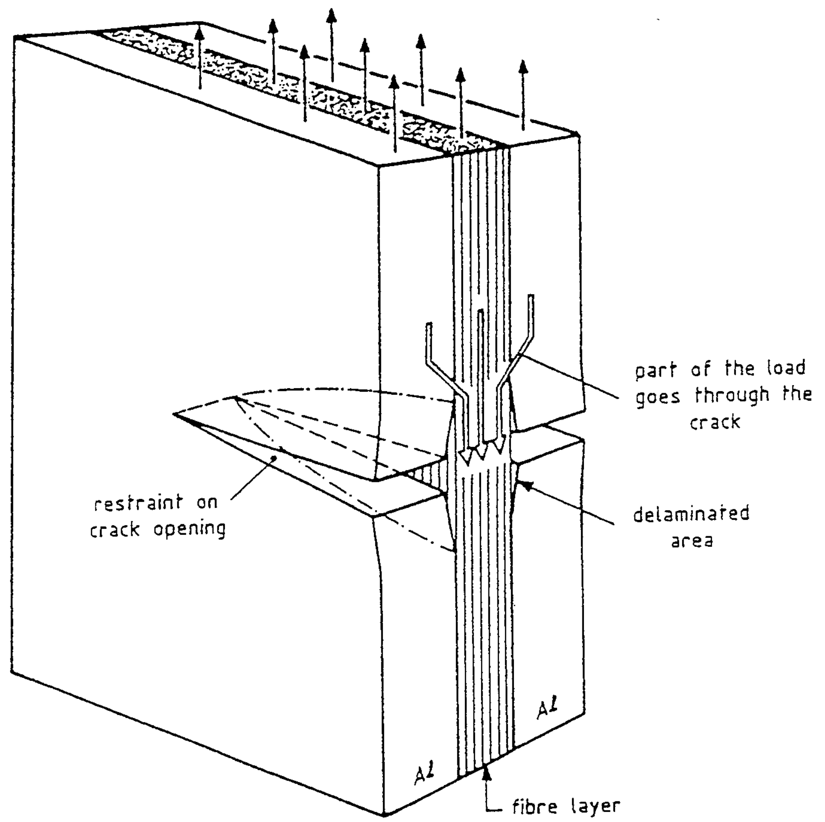


Figure 2: The fatigue crack growth behaviour of GLARE

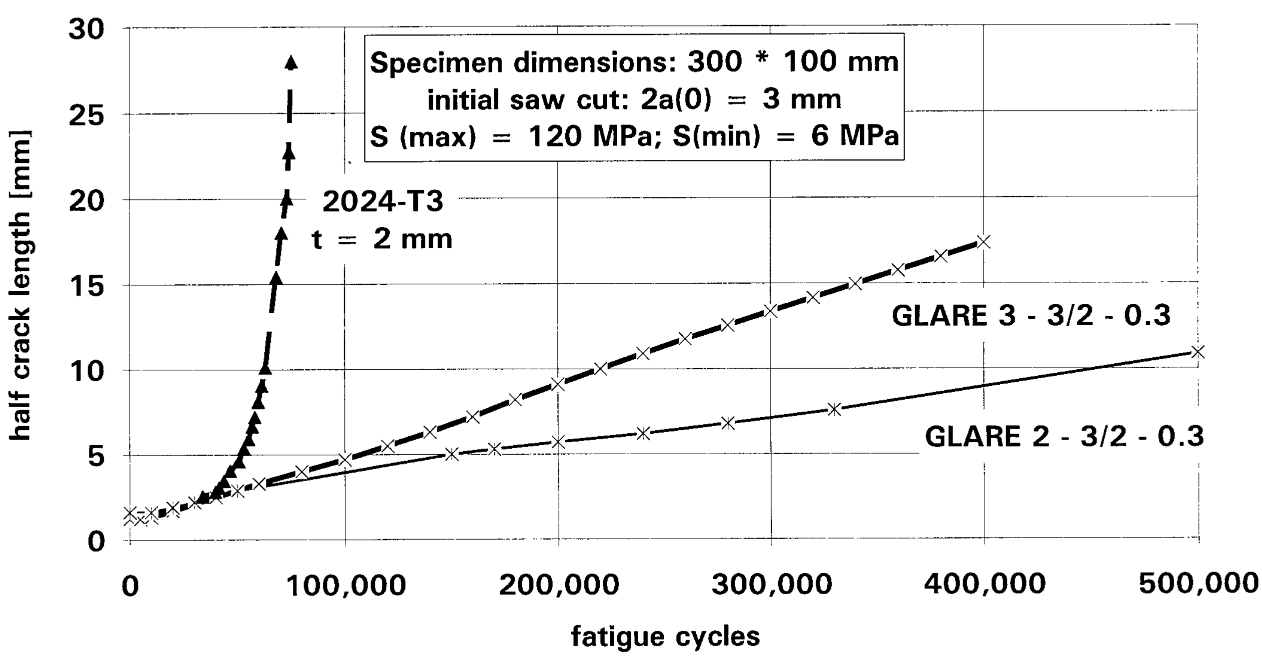


Figure 3: Fatigue behaviour of riveted lap joint

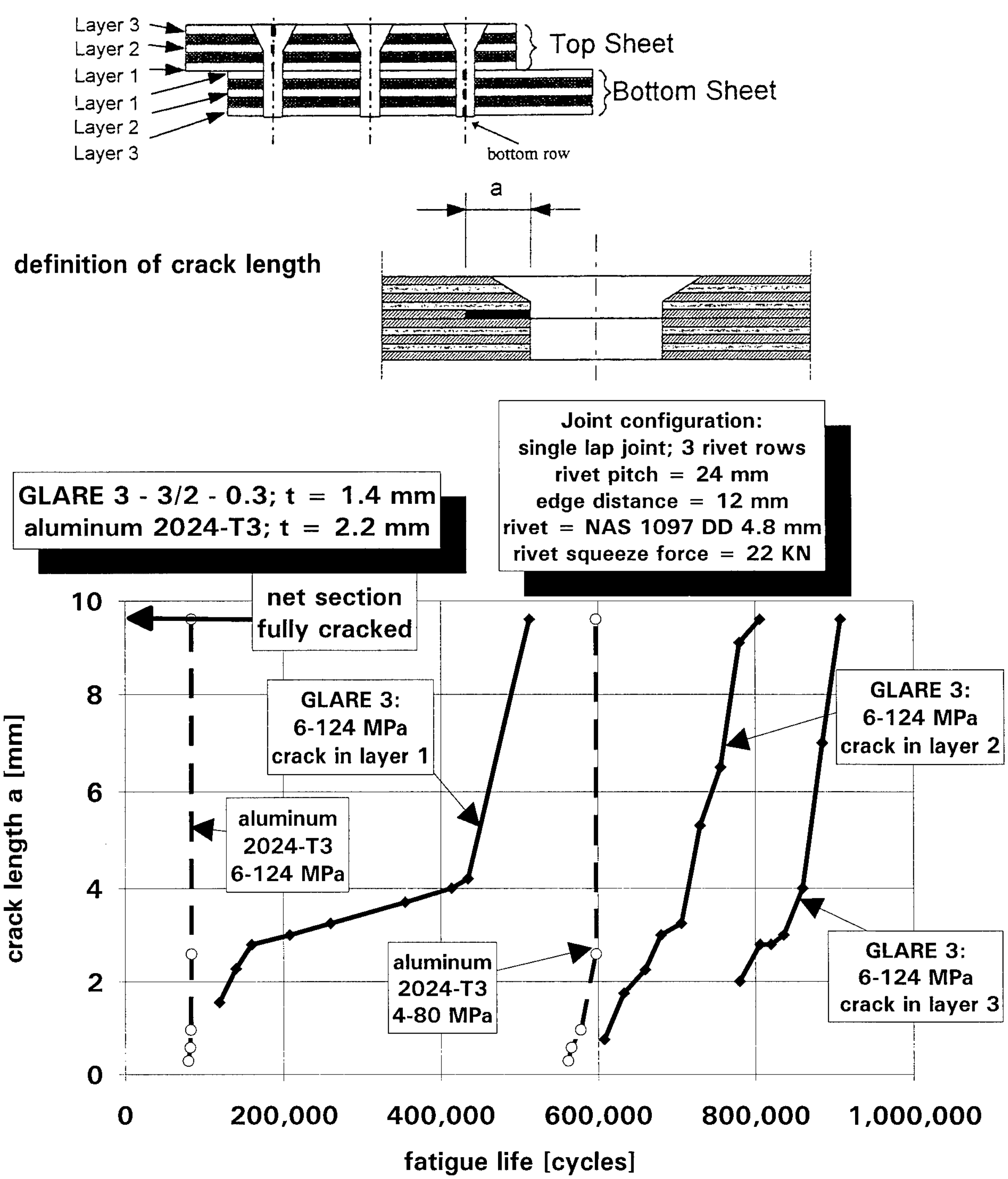


Figure 4: Influence of crack growth behaviour on inspection intervals

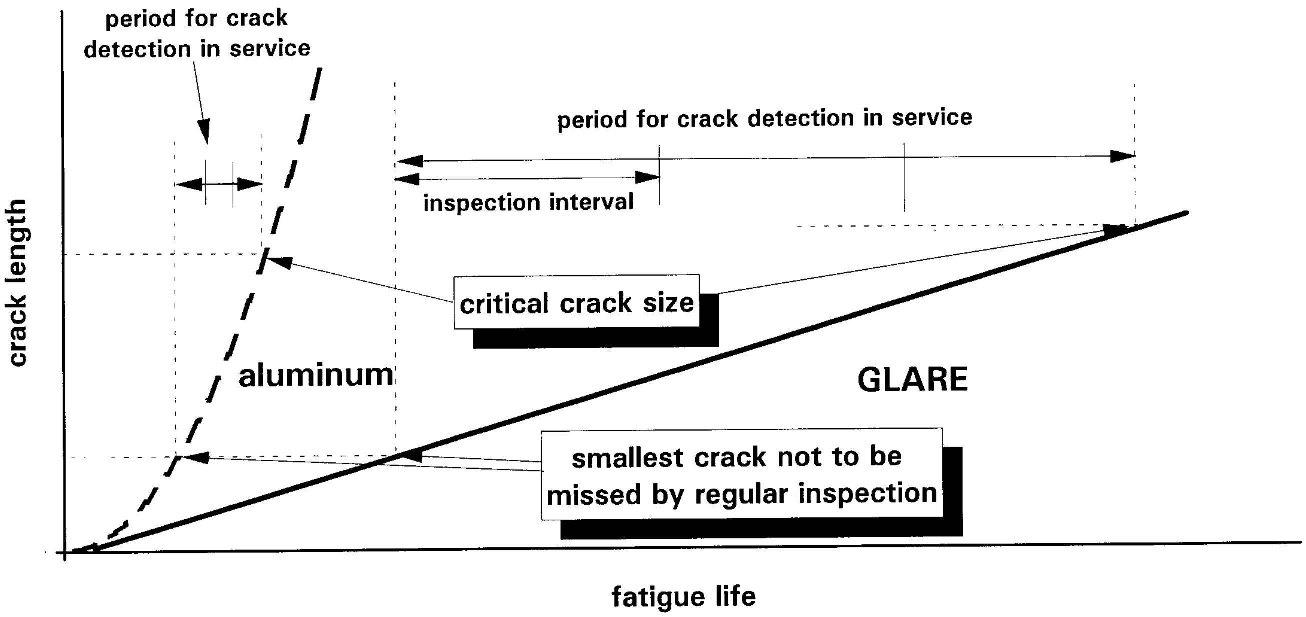
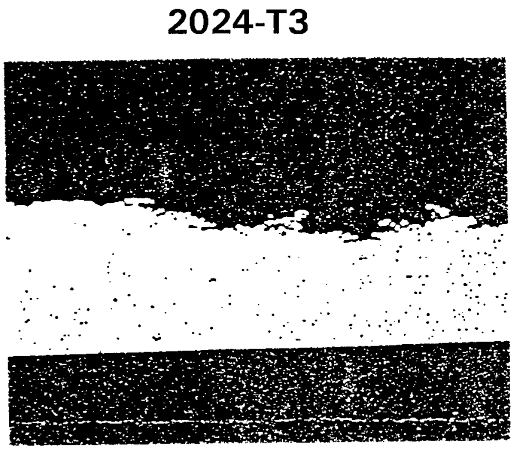
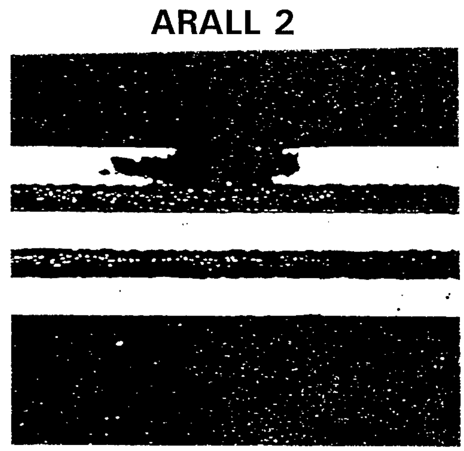


Figure 5: Comparison of corrosion attack



Photomicrograph (20*) showing the deep corrsion (0.4 mm) on monolithic 2024-T3 sheet (1.2 mm) exposed 4 weeks to the MASTMAASIS test



Photomicrograph (20*) showing the corrosion perforated the outer aluminum layer of the laminate after 4 weeks exposure to the MASTMAASIS test The prepreg layer prevented the corrosion from penetrating through the thickness of the laminate

Figure 6: Fatigue crack growth initiated by corrosion pits.

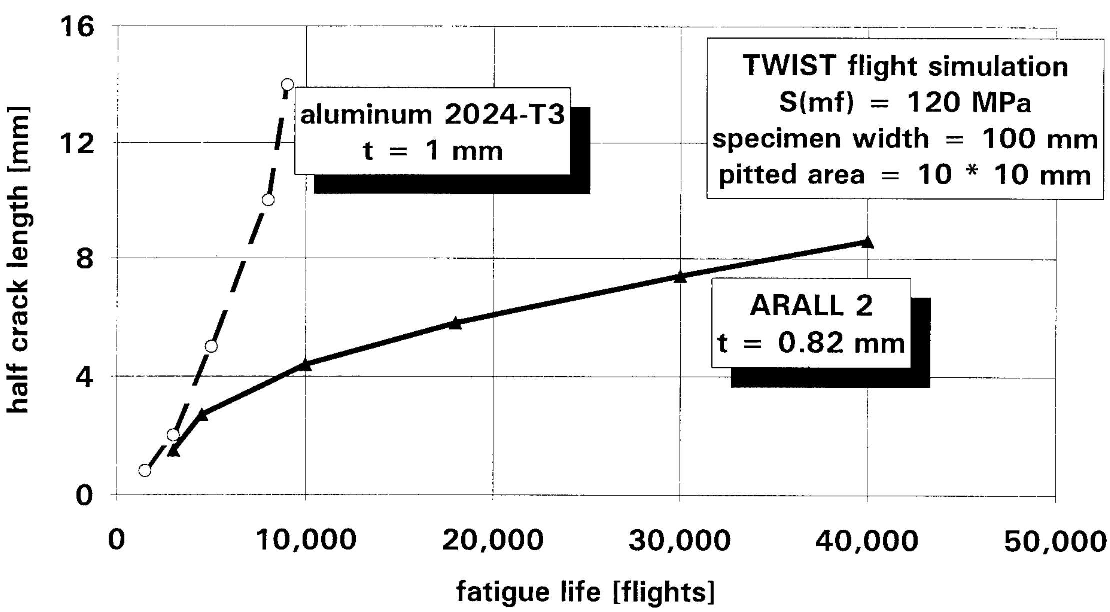


Figure 7: FAR 25.855

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
STATEMENT OF COMPLIANCE WITH THE FEDERAL AVIATION REGULATIONS

DATE: March 28, 1994

AIRCRAFT OR AIRCRAFT COMPONENT IDENTIFICATION

MAKE	MODEL NO.	TYPE (Airplane, Radio, Helicopter, etc.)	NAME OF APPLICANT
Boeing	All	Airplane	Structural Laminates Company

LIST OF DATA

IDENTIFICATION | TITLE

SMT Work Request 94-00716

Oil Burner Cargo Liner Test

Description	Flame Penetration	Peak Temp.
.025 2/1 Glare 012214470	No	187°F
.031 2/1 Glare 01221C472	No	185°F
.036 2/1 Glare 012218471	No	174°F
.044 3/2 Glare 01221D473	No	171°F
.054 3/2 Glare 01221E474	No	181°F

PURPOSE OF DATA

To show compliance with the burn through requirements for cargo liner materials

APPLICABLE REQUIREMENTS (List specific sections)

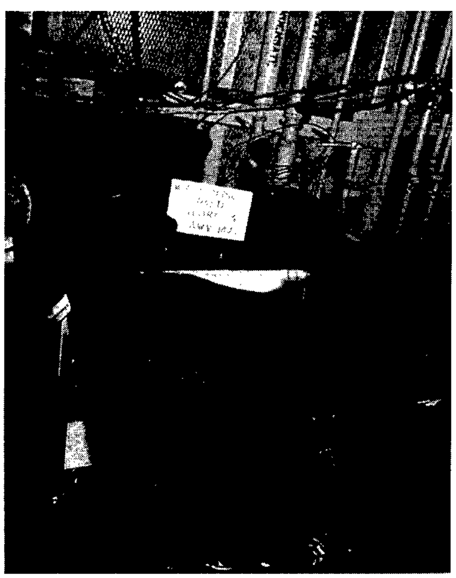
FAR 25.855(c) Amendment 72

CERTIFICATION - Under authority vested by direction of the Administrator and in accordance with conditions and limitations of appointment under Part 183 of the Federal Aviation Regulations, data listed above and on attached sheets numbered ______ have been examined in accordance with established procedures and found to comply with applicable requirements of the Federal Aviation Regulations.

I (We) Therefore
[ ] Recommend approval of these data
[x] Approve these data

SIGNATURE(S) OF DESIGNATED ENGINEERING REPRESENTATIVE(S)	DESIGNATION NUMBER(S)	CLASSIFICATION(S)
[signature]	NM-1539	Interior Materials Flammability

Figure 8: GLARE 3 sheet after 15 minutes exposure to 1100 C flame (courtesy Boeing)



top view

bottom view

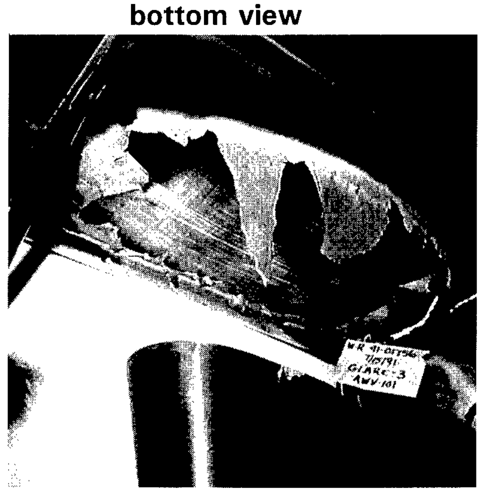


Figure 9: puncture behaviour of GLARE and conventional materials

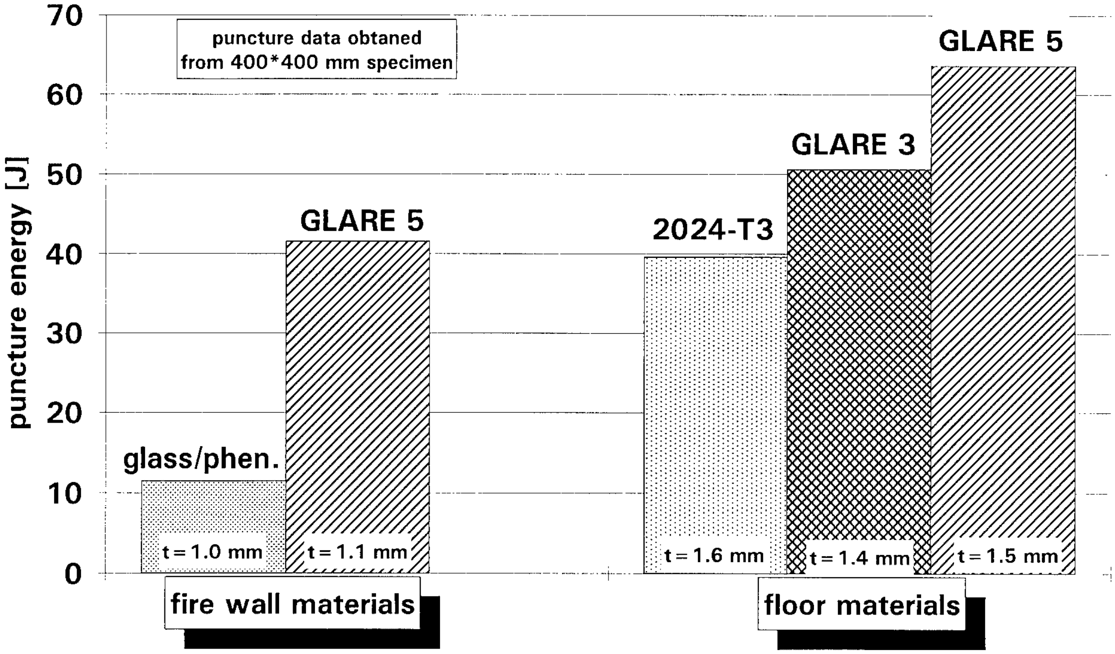


Figure 10: GLARE 3 bulk cargo floor after 2 years and 8 months of flight evaluation (courtesy US Air)

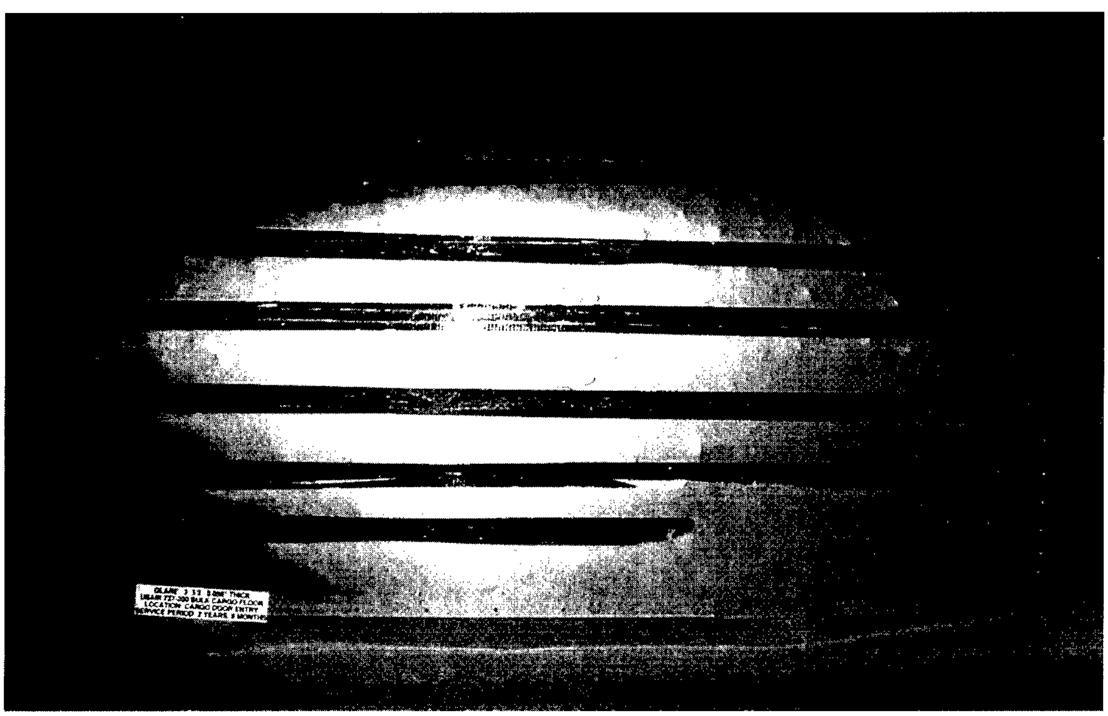


Figure 11: Strain rate effect on tensile strength of GLARE 3

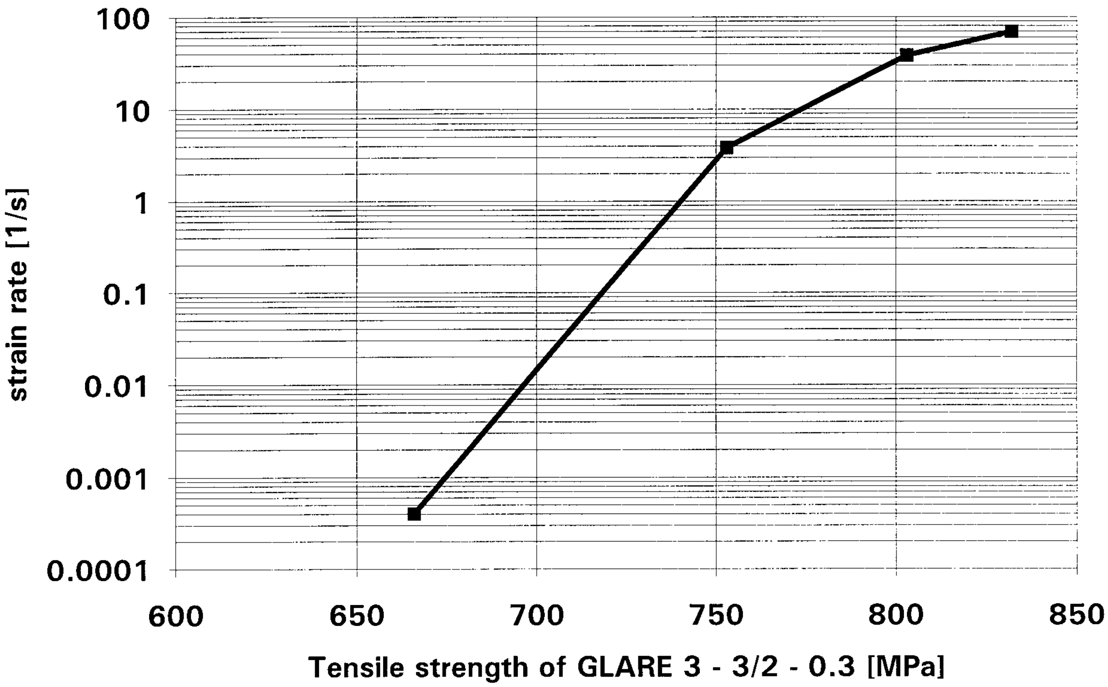
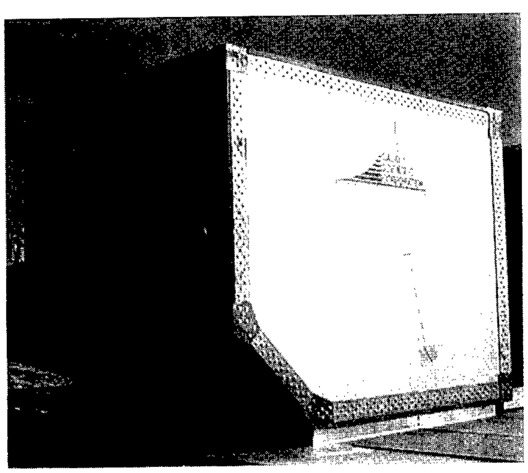


Figure 12: Explosion and fire resistant GLARE cargo container

before explosion



after explosion

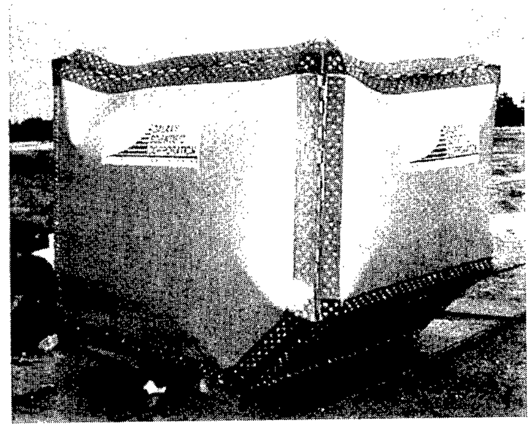


Figure 13: Garuda DC 10 accident in Japan at June 13, 1996

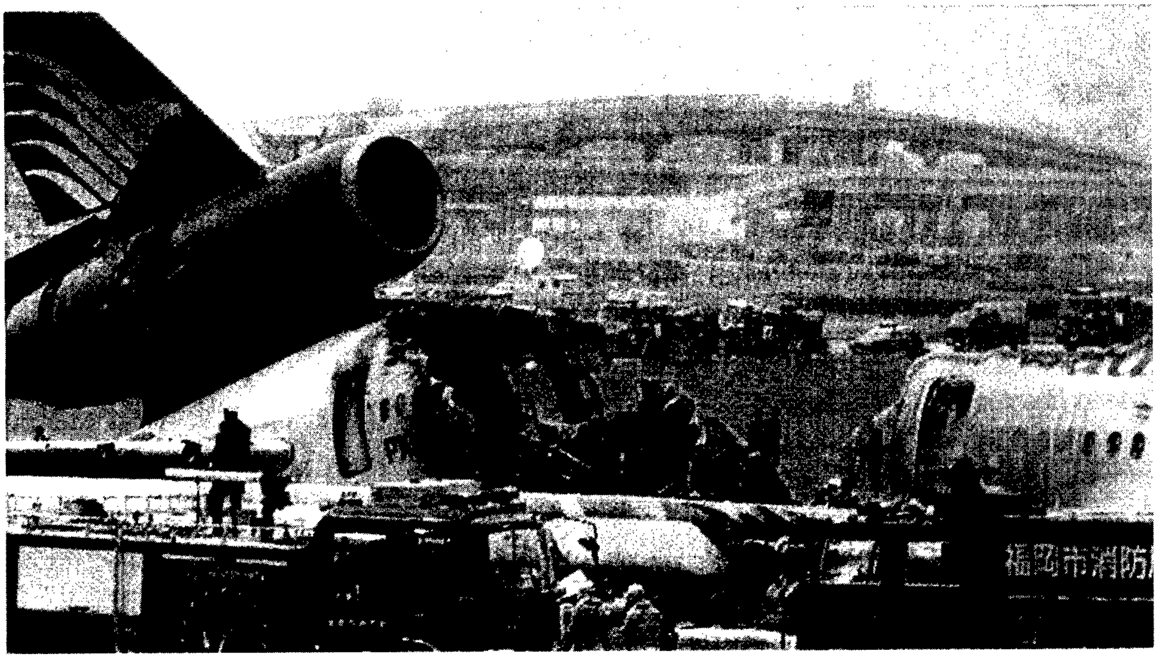


Figure 14: C-130 accident in The Netherlands at July 15, 1996

DISCUSSION - PAPER NO. 26

J. Andrews (Question)

What are the problems of forming or deep drawing GLARE material?

G.H.J.J. Roebroeks - Author/Speaker (Response)

The important items to address are:

- failure strain of the glass fibres (4.5%)
- build-up of internal stresses
- micro cracking of the adhesive.

The GLARE materials allow forming of most standard geometries (stringers, fuselage skin, slightly double-curved parts). For "severely" double-curved parts, solutions are available.

P. Derouet (Question/Comment)

During fire tests of GLARE 3 / GLARE 2 panels, have you conducted the test with vibrations? Because the behaviour of composite materials during fire are very different with versus without vibrations (FAA fireproofness advisory circulars, AC 20-135 - or others? - require vibration). I think GLARE is very interesting for engine cowlings application.

G.H.J.J. Roebroeks - Author/Speaker (Response)

No, we have not included vibrations. The tests we did are standard tests for cargo liner materials. Your question is related to the question whether fire resistant materials having structural requirements/functions also carrying structural loads, should be tested having the actual loads on the material. Since this aspect is not in any requirement (as far as I know), the problem is how to define the proper condition (vibration/load).

K. Stellbrink (Question)

Have you ever considered the application of fibre-reinforced thermoplastics instead of epoxy as interleaf material?

G.H.J.J. Roebroeks (Response)

Yes! The reason to do so was/is twofold:

- higher temperature capabilities (>150°C constant use temperature - HSCT).
- potential improved forming properties when, during forming, increased temperatures are applied (close to the T_g of the adhesive.

This last item has not been shown to work yet (thermoplastics under consideration are PEEK & PEI).

NEW FIRE SAFE MATERIAL FOR CABIN INTERIORS

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1. SUMMARY

The fire response of a potassium aluminosilicate matrix (GEOPOLYMER) carbon fiber composite was measured and the results compared to organic matrix composites being used or considered for aircraft cabin interior applications. At irradiance levels of 50 kW/m^2 typical of the heat flux in a well developed cabin fire, glass- or carbon-fiber reinforced polyester, vinylester, epoxy, bismaleimide, cyanate ester, polyimide, phenolic, and engineering thermoplastic laminates ignited readily and released appreciable heat and smoke, while carbon-fiber reinforced GEOPOLYMER composites did not ignite, burn, or release any smoke even after extended heat flux exposure. The GEOPOLYMER matrix carbon fiber composite retains sixty-three percent of its original flexural strength after a simulated large fire exposure.

2. INTRODUCTION

Fire performance severely limits the use of low cost polymer composites in civil aircraft interiors [1,2] and public transportation [3]. Moreover, the addition of flame retardant chemicals to flammable polymers to enable them to qualify for use in aircraft interiors has been correlated with enhanced corrosion of aluminum structural alloys in contact with these materials [4]. Although significant progress has been made in recent years to develop high service temperature, fire resistant fibers from boron, silicon carbide, and ceramics [5], parallel work on intrinsically fire resistant, low cost, matrix materials to bind the fibers has not kept pace. Consequently, affordable, low-temperature processable matrix materials for fire resistant composites are currently unavailable since most organic polymers soften and ignite at temperatures of 400-600°C characteristic of fuel fire exposure conditions.

The Federal Aviation Administration has recently initiated a research program to develop low-cost, environmentally-friendly, fire resistant matrix materials for use in aircraft composites and cabin interior applications [6]. The flammability requirement for new materials is that they withstand a 50 kW/m^2 incident heat flux characteristic of a fully-developed aviation fuel fire penetrating a cabin opening, without propagating the fire into the cabin compartment [7]. The goal of the program is to eliminate cabin fire as cause of death in aircraft accidents. However, voluntary adoption of the new materials technology by aircraft and cabin manufacturers requires that it be cost effective to install and use, so it is expected that these new aircraft materials will be broadly applicable in transportation and infrastructure where a high degree of intrinsic fire resistance is needed at low to moderate cost. To this end we are evaluating a new, low-cost, inorganic polymer derived

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from the naturally occurring geological materials– silica and alumina– hence the name GEOPOLYMER.

3. MATERIALS

The GEOPOLYMER matrix resin being evaluated for interior and secondary composites is a potassium aluminosilicate, or poly(sialate-siloxo), with the general chemical structure:

$$K_n\{-(SiO_2)_z-AlO_2\}_n \bullet wH_2O \qquad (1)$$

where, z >> n. This particular resin hardens to an amorphous or glassy material at moderate temperatures and is one of a family of inorganic GEOPOLYMER materials described previously [8,9]. The GEOPOLYMER resin used in the present study was prepared by mixing 100 g of caustic aqueous liquid, 135 g of powder, 10 g of water, and 1 g of aqueous surfactant solution for one minute at room temperature in a food processor. Cross-ply [0/90] composite laminates were fabricated by hand rolling the deaerated GEOPOLYMER liquid resin into a 0.193 kg/m^2 (5.7 oz/yd^2), 3K plain weave, Amoco T-300, carbon fabric and air drying 30 seconds at 80°C to remove residual moisture and develop tack. Approximately 25 plies were then cut, stacked, and cured in a vacuum bag at 80°C in a heated press with 0.3 MPa pressure for three hours. The panels were then removed from the vacuum bag and dried for an additional 12 hours at 80°C or until constant weight was achieved. Final thickness of the crossply laminates was a uniform 5.6-mm and the density was 1.85 g/cm^3. Visual inspection of cut edges revealed that the laminates were substantially free of large voids. Hand impregnation and layup resulted in a fiber volume fraction of approximately 45% in the GEOPOLYMER laminates.

Organic matrix crossply laminates of polyester (PE), vinylester (VE), epoxy (EP), cyanate ester (CE), bismaleimide (BMI), PMR-15 polyimide (PI), and phenolic (PH), thermoset resins as well as thermoplastic polyphenylene sulfide (PPS), polyetheretherketone (PEEK), polyetherketone- ketone (PEKK), polyarylsulfone (PAS), and polyethersulfone (PES) resin matrices were prepared from commercial S-glass, E-glass or carbon fabric prepregs. The details of material composition and fabrication have been described elsewhere [10-12]. Some of the phenolic laminates were hand impregnated [13] and contained only about 34 volume percent fiber compared to a nominal 60 percent fiber volume for all of the commercial prepreg materials. The density of these cured laminates ranged from about 1.55 to about 1.98 g/cm^3 at the nominal 60 volume percent carbon and glass fiber loading, respectively.

4.0 METHODS

4.1 Ignitability, Heat Release, and Smoke

Peak heat release rate, 300-second average heat release rate, total heat release, mass loss during burning, ignitability (time-to-ignition), and the specific extinction area of smoke produced were measured according to ASTM E-1354 in an oxygen consumption calorimeter employing a conical radiant heater to provide 50 kW/m^2 of radiant energy to the surface of a 10-cm by 10-cm sample having a nominal thickness 6-mm. The sample is positioned horizontally on a weighing device with a spark igniter 2.54-cm above the surface to ignite combustible vapors (piloted ignition). The mass flowrate of air past the burning sample is measured as well as the amount of oxygen consumed from the air stream by the combustion process and these measurements are used to calculate the heat release rate (HRR) of the burning material using a factor of 13.1 kJ of heat produced per gram of oxygen consumed [14].

4.2 Flame Spread Index

Flame spread across a surface is one measure of the propensity of a material to propagate a fire. Downward flame spread was measured according to ASTM E-162-83 after ignition of a 15-cm by 46-cm sample by a radiant heat source. Only the combustible organic matrix composites were tested in this procedure as the GEOPOLYMER sample would not support flaming combustion.

4.3 Residual Flexural Strength

Specimens were tested for flexural strength before and after the fire test to determine the residual strength of the composite panels after fire exposure according to ASTM D-790. Specimens having dimensions 7.6-cm by 7.6-cm were exposed to a 25 kW/m^2 radiant heat source for a duration of 20 minutes according to ASTM E-662 protocol for smoke generation in a

flaming mode. The panels were reclaimed and 5 coupons, 1.27-cm wide by 7.6-cm long were cut from each for flexural testing on a universal testing machine. The GEOPOLYMER composites were not subjected to the ASTM E-662 protocol because they would not burn. Instead a more severe test was used wherein panels were exposed to a 400°C oxidizing environment for 60 minutes [15], which is the equivalent surface temperature for a 25 kW/m^2 radiant energy exposure in air compared. The original sample thickness was used to calculate the residual flexural strength for all samples after the fire test.

5. RESULTS AND DISCUSSION

Table 1 summarizes all of the cone calorimeter data for the composite specimens. Individual values for percent weight loss during the fire test, time to ignition, peak heat release rate, 300-second average heat release rate, total heat released per unit area, and specific extinction area of smoke are reported for each material. Average values of these fire parameters were calculated for families of the organic materials grouped together according to chemistry (condensation/ phenolics, addition/thermosets), physical properties (engineering thermoplastics), or end-use applications (high temperature/ advanced thermosets). It is seen that this somewhat arbitrary grouping leads to variations within groups which can be greater than the variation between groups. However the averages are fairly representative of each type of material, and it is clear that the GEOPOLYMER composite is non-combustible while all of the organic polymer matrix composites support flaming combustion. It was noted that the GEOPOLYMER resin became white (crystallized) after fire exposure but did not ignite or smoke even after ten minutes in the cone calorimeter.

It is important to try to understand how or if the fire parameters in Table 1, measured in a small scale bench test, relate to the actual fire hazard of a composite material in the use environment. This is a very difficult task and it is important to realize that no single parameter will provide the best estimation of the fire hazard of a material because the hazard depends to a large extent on where and how the material is used (e.g., enclosed space, open space, structural, non-structural, etc.).

It has been suggested that heat release rate of a material measured in small scale tests under simulated radiant exposure conditions is the single most important parameter in characterizing the hazard of a material in a fire [16]. Recently, it was shown that a combined parameter which is the ratio of the peak heat release rate to the time to ignition, also known as the flame propagation index (FPI) or flashover parameter in units of kW/m^2-s, is a more accurate predictor of time-to-flashover in both room and aircraft compartment fires because it more accurately accounts for thickness effects of the material [17]:

$$\mathrm{FPI} = \frac{\text{Peak Heat Release Rate (kW/m}^2\text{)}}{\text{Time–to–ignition (seconds)}} \qquad (2)$$

Flashover is a phenomenon unique to compartment fires where incomplete combustion products accumulate at the ceiling and ignite causing total involvement of the compartment materials and signaling the end to human survivability. Consequently, in a compartment fire the *time to flashover* is the time available for escape and this is the single most important factor in determining the fire hazard of a material or set of materials in a compartment fire. The Federal Aviation Administration has used the time-to-flashover of materials in aircraft cabin tests as the basis for a heat release and heat release rate acceptance criteria for cabin materials for commercial aircraft [6]. Figure 1 shows the calculated time to flashover of the 6-mm thick composite material groups from Table 1 if they were used as wall linings in an 8 ft x 12 ft room which is 8 feet high. The equation used to calculate the time to flashover from the peak heat release rate / time to ignition ratio (FPI) from Table 1 is [17]

$$\text{Time-to-Flashover (s)} = 991–629 \log_{10}\mathrm{FPI} \qquad (3)$$

Equation 3 provided the best fit ($r^2 = 0.94$) to all of the EURIFIC full scale fire test data [18] for 13 different lining materials obtained according to ISO 9705 corner wall/room fire test using the 100/300 ignition option (100 kW fire for 10 minutes + 300 kW fire for additional 10 minutes) in the corner of a 3.6-m long x 2.4-m wide by 2.4-m high room. For comparison to the

predicted behavior of the composite materials in Figure 1, materials in the ISO 9705 test with 10-12 minute flashover times include a melamine high pressure laminate on non-combustible board, steel faced polymeric foam with mineral wool backing, fire-retardant PVC on gypsum wallboard, fire retardant particle board, and a fire retardant textile on gypsum wallboard.

The calculated values for time-to-flashover of organic and GEOPOLYMER composites in a full scale room test shown in Figure 1 provide a qualitative ranking of the fire hazard of these materials in a compartment. The engineering thermoplastics are predicted not to reach flashover during the 20 minute ignition period but could generate appreciable smoke, while the GEOPOLYMER composite will never ignite, reach flashover, or generate any smoke in a compartment fire. It is possible that the actual time to flashover of the continuous fiber reinforced composite laminates listed in Table 1 would be significantly different from the calculated values displayed in Figure 1 and full-scale validation tests of these materials are planned.

The flame spread index provides a relative measure of the speed at which the flame front of a burning composite travels. Consequently the flame spread index provides a qualitative ranking of the rate of fire growth in an open environment. Figure 2 shows a plot of the ratio of the peak heat release rate / time-to-ignition (FPI) from Table 1 for selected materials which were also tested for flame spread index. The correlation is seen to be very good between the flame propagation index determined in the bench scale cone calorimeter test and the measured ASTM E-162 flame spread index for these cross-ply composite laminates. According to this plot, the GEOPOLYMER composite would have a flame spread index of zero, indicating that the GEOPOLYMER composite would be an excellent fire barrier.

Perhaps the most important fire response parameter for infrastructure applications is the residual strength of the composite after fire exposure. Comparison of the composite resin categories on the basis of percent residual flexural strength retained after the fire exposure is shown in Figure 3. The values represent a combined average for the thermoset (vinylester, epoxy), advanced thermoset (BMI, PI), phenolic, and engineering thermoplastic (PPS, PEEK). As mentioned previously, the carbon fiber reinforced GEOPOLYMER crossply laminate was subjected to a much more severe thermal environment (800°C/75 kW/m^2) than the organic composites but still retains 63% of its original 245 MPa flexural strength. By way of comparison the original flexural strength of the carbon fiber reinforced phenolic resin crossply laminate was 283 MPa. Failure mode in the GEOPOLYMER composite flexural test was a shear delamination near the neutral axis corresponding to a maximum shear stress at failure of about 13 MPa.

Table 2 compares some thermomechanical properties of fiber reinforced concrete [19,20], structural steel [20,21], a 7000-series aluminum [22] used in aircraft structures, and the Geopolymer-carbon fiber composite laminate [8]. Maximum temperature capability is defined as the temperature in air at which Young's modulus falls to one-half of its room temperature value. The Geopolymer-carbon fiber composite, even in the prototype configuration tested, significantly outperforms fiber reinforced concrete with regard to flexural strength and surpasses concrete and structural steel in temperature capability. It is hypothesized that the observed ≥800°C temperature capability of the GEOPOLYMER composite in air is the result of protection of the carbon fibers from oxidation by surface chemical reactions with the aluminosilicate matrix at elevated temperature.

Specific flexural strength is the flexural strength of the material divided by the bulk density and is the figure of merit for weight-sensitive applications such as aircraft and surface transportation vehicles. The Geopolymer composite is superior to all of the materials listed including aircraft-grade aluminum, with respect to specific strength. The inorganic Geopolymer resin composite is comparable in strength to polymer matrix composites but is totally non-combustible. Figure 4 shows the relationship between specific strength and approximate materials cost for the materials listed in Table 2. It is clear that cost increases exponentially with specific strength. However, the higher cost of materials used in air and ground transportation vehicles is offset by fuel savings over the

operating life of the vehicle. The cost of the prototype Geopolymer composite is presently on the order of fifty dollars per pound– ninety-eight percent of which is the cost of the intermediate-modulus carbon fabric which comprises a nominal sixty percent of the composite volume. The Geopolymer resin itself costs about two dollars per kilogram.

6. CONCLUSIONS

Carbon fiber reinforced potassium aluminosilicate resin (GEOPOLYMER) composites are noncombustible, nontoxic, noncorrosive structural materials which are ideally suited for aircraft interior applications such as cargo liners, honeycomb interior panels, floor beams, fire barriers, etc., where a combination of low temperature processing, fire endurance, non-combustibility, and specific flexural strength is needed. Carbon fabric reinforced GEOPOLYMER crossply laminates have comparable strength to fabric reinforced organic resin composites and better strength retention after fire exposure. In comparison to structural steel the Geopolymer composite falls short in flexural strength, modulus, and cost but the temperature capability is superior. Consequently in applications requiring fire endurance, replacement cost or the added cost of a fire barrier must be figured into the material cost for metallic structures.

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Keywords: Aluminosilicate, ceramic composite, fire, fire barrier, cone calorimeter, fire hazard, flame spread, flammability, flexural strength, GEOPOLYMER, heat release, smoke.

Table 1.
Fire Calorimetry Data for Crossply Laminates at 50 kW/m^2 Irradiance [10-12]

RESIN	FIBER	Weight Loss	Time to Ignition	Peak HRR	300s Average HRR	Total Heat Release	Smoke
		%	Seconds	kW/m^2	kW/m^2	MJ/m^2	m^2/kg
Isophthalic polyester	Glass	–	77	198	120	–	378
Vinyl Ester	Glass	–	78	222	158	–	861
Vinyl Ester	Glass	26	74	119	78	25	1721
Epoxy	Glass	–	105	178	98	30	580
Epoxy	Glass	19	18	40	2	29	566
Epoxy	Glass	28	49	181	108	39	1753
Epoxy	Glass	22	50	294	135	43	1683
Epoxy	Carbon	24	94	171	93	–	–
THERMOSETS		**24**	**68**	**175**	**99**	**33**	**1077**
Cyanate Ester	Glass	22	58	130	71	49	898
PMR-15 polyimide	Glass	11	175	40	27	21	170
Bismaleimide	Glass	25	141	176	161	60	546
ADVANCED THERMOSETS		**19**	**124**	**115**	**86**	**43**	**538**
Phenolic	Glass	–	210	47	38	14	176
Phenolic	Glass	12	214	81	40	17	83
Phenolic	Glass	6	238	82	73	15	75
Phenolic	Glass	10	180	190	139	43	71
Phenolic	Glass	3	313	132	22	12	143
Phenolic	Carbon	28	104	177	112	50	253
Phenolic	Carbon	9	187	71	41	14	194
PHENOLICS		**11**	**206**	**111**	**66**	**23**	**142**
Polyphenylenesulfide	Glass	13	244	48	28	39	690
Polyphenylenesulfide	Carbon	16	173	94	70	26	604
Polyarylylsulfone	Carbon	3	122	24	8	1	79
Polyethersulfone	Carbon	–	172	11	6	3	145
Polyetheretherketone	Carbon	2	307	14	8	3	69
Polyetherketoneketone	Carbon	6	223	21	10	15	274
ENGINEERING PLASTICS		**8**	**207**	**35**	**22**	**15**	**310**
GEOPOLYMER	Carbon	**0**	∞	**0**	**0**	**0**	**0**

Table 2. Typical Properties of Structural Materials

MATERIAL	Young's Modulus	Density	Flexural Strength	Specific Flex Strength	Temperature Capability
	GPa	kg/m^3	MPa	$MPa\text{-}m^3/kg$	°C
Fiber-Reinforced Concrete	30	2300	14	0.0058	400
Structural Steel	200	7860	400	0.0525	500
Aircraft Aluminum	70	2700	275	0.102	300
Geopolymer-Carbon Fiber Composite	45	1900	245	0.129	≈ 800

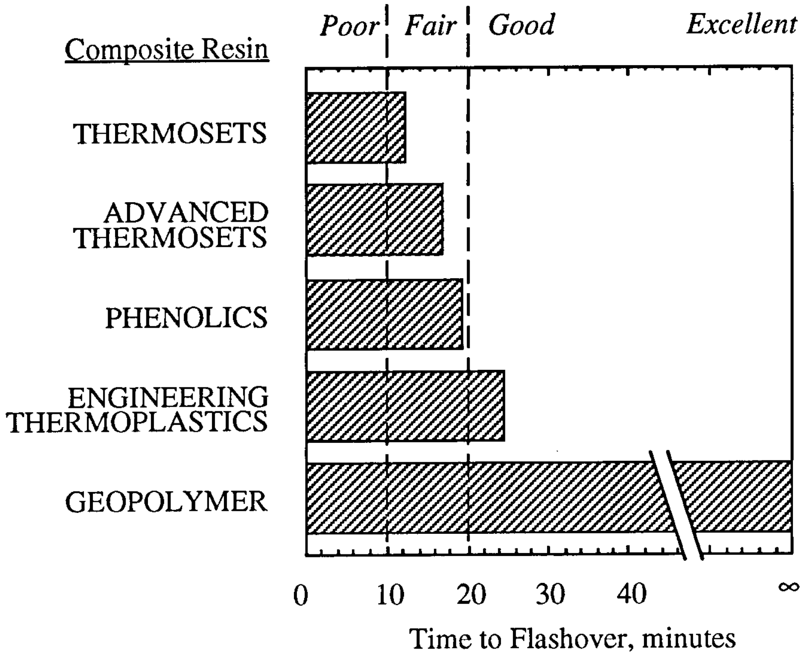

Figure 1. Predicted time to flashover in ISO 9705 corner/room fire test with various structural composites as wall materials.

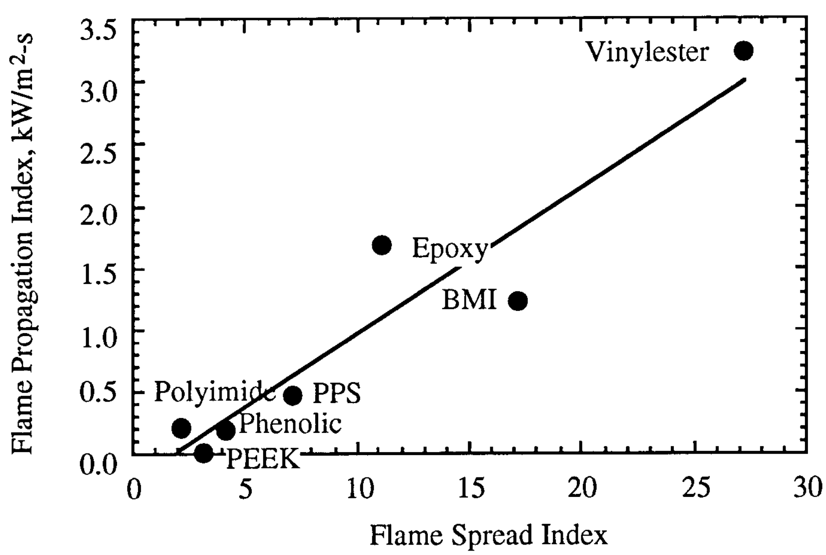

Figure 2. Flame Propagation Index at 50 kW/m^2 incident flux *versus* Flame Spread Index for a number of glass-reinforced organic polymer composites.

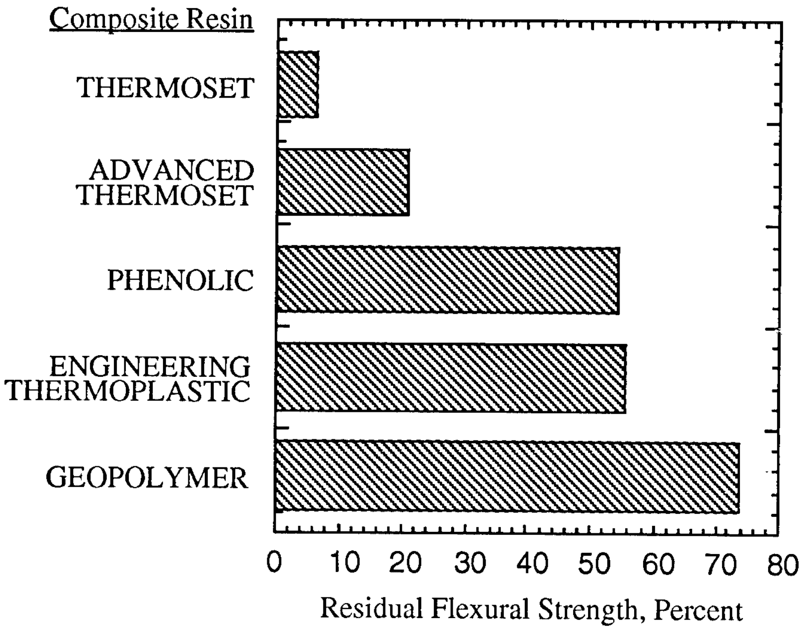

Figure 3. Residual Flexural Strength of Cross-ply Laminates after Fire Exposure

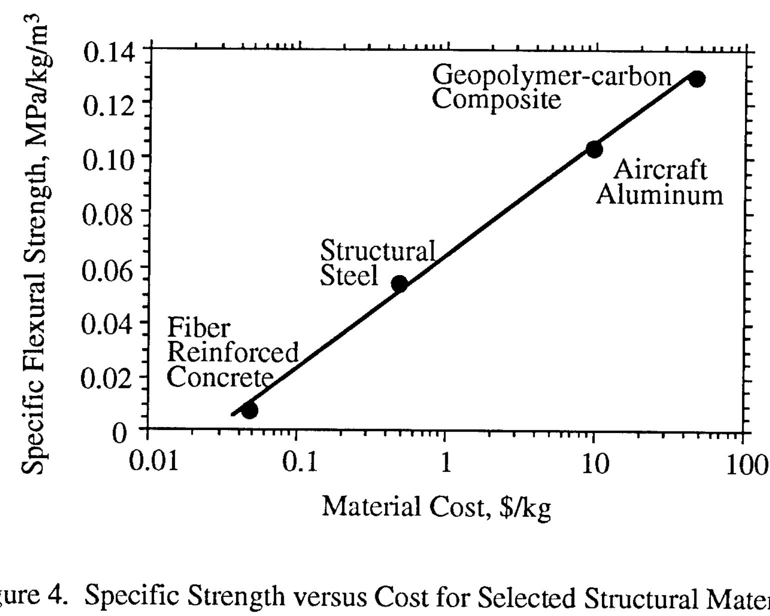

Figure 4. Specific Strength versus Cost for Selected Structural Materials

TOXICITE DES PRODUITS DE COMBUSTION DE MATERIAUX UTILISES DANS L'AMENAGEMENT CABINE
UNE METHODE D'EVALUATION SIMPLIFIEE

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1. RESUME

Lors du 73ième symposium AGARD qui s'est tenu à SINTRA en 1989, nous avions présenté une méthodologie associant un modèle feu original et un protocole expérimental permettant d'apprécier d'une part la réaction au feu des matériaux par des critères physico-chimiques et d'autre part la toxicité des produits de combustion par des critères biologiques mesurés sur souris. Une méthode de classement des matériaux avait été proposée.

Sur les bases de cette méthodologie, les données recueillies sur 6 matériaux d'aménagement cabine ont permis de mettre en évidence une relation entre la perte de masse, donc la quantité de matière dégradée et le temps d'incapacitation chez l'animal.

Cette incapacitation est le premier effet biologique mesurable limitant la fuite des personnes exposées aux dégagements toxiques dans un incendie de cabine. Cet effet est directement lié au dégagement massif de CO, gaz narcotique principal responsable du phénomène. Si la concentration de CO dégagé est elle-même directement liée à la quantité de matière dégradée, il reste à connaître la nature des effets combinés des autres gaz, issus de la combustion des matériaux. Des études ont montré que la combinaison des effets des toxiques majeurs se traduit généralement par une relation d'additivité renforcée par un effet de synergie dû essentiellement à la présence de CO_2 (entre 5% et 8% en volume) produit massivement au cours des incendies. Au vu de ces résultats, il semble donc que l'enregistrement de la perte de masse serait un des moyen représentatifs de l'évaluation du potentiel toxique des matériaux, en terme d'incapacitation.

Ainsi il resterait à définir un critère de sélection des matériaux reposant :

- soit sur le temps auquel le débit massique est maximum
- soit sur un pourcentage limite de perte de masse à un temps donné.

2. INTRODUCTION

Le potentiel toxique d'un matériau peut être relié à de multiples données analytiques prenant en compte la présence de plusieurs toxiques et leurs effets combinés. Toutefois avant le seuil de létalité, les produits de décomposition thermique des matériaux provoquent un effet incapacitant, premier critère biologique identifié lié à l'impossibilité de fuite des personnes exposées. Il était interessant de regarder si, à partir d'un modèle feu permettant de mesurer simultanément des paramètres physico-chimiques et des paramètres biologiques, l'incapacitation était reliée à un paramètre plus facile à mesurer et représentatif de la dégradation thermique du matériau.

C'est ce qui a été réalisé dans le modèle feu "mini corner test" (figure n°1) dont les conditions de thermolyse permettent une montée balistique en température qui, comparée aux modèles à température constante, est plus représentative de conditions d'incendie. Le CEAT y a étudié le comportement au feu des matériaux de cabine d'avion sous les deux aspects suivants :

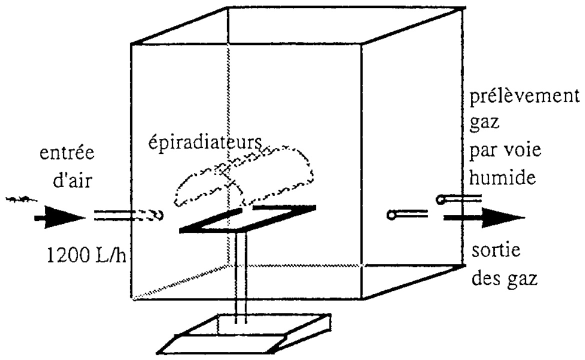
- l'aspect physico-chimique en mesurant : l'inflammation, la perte de masse, le dégagement calorique, l'émission des fumées, l'analyse des toxiques majeurs,
- l'aspect biologique en mesurant : l'incapacitation, la mortalité.

3. PARTIE EXPERIMENTALE

3.1 APPAREILLAGE

Afin de suivre la cinétique de la dégradation thermique, la perte de masse a été enregistrée sur la durée de l'essai.
l'analyse des résultats nous a conduit à développer l'étude qui fait l'objet de ce document :
L'étude des interdépendances entre un paramètre physico-chimique, la perte de masse et un paramètre de nature biologique, l'apparition de l'incapacitation.

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.



four "MINI CORNER TEST"
figure. n°1

3.2 CONDITIONS D'ESSAI

Durée de l'essai : 15minutes
échantillons : de 5 à 15g. 3 masses différentes par matériau.
Ventilation : renouvelement de l'atmosphère de l'enceinte toutes les trois minutes (conditons aéronautiques) soit pour un volume de 64 litres, un débit de 1200 litres par heure.

Thermolyse (figure n°2) : montée en température de 40°C par minute pendant 6 minutes puis de 10°C par minute pour atteindre 350°C à la surface de l'échantillon.

tracé température/temps au dessus
du porte-échantillon

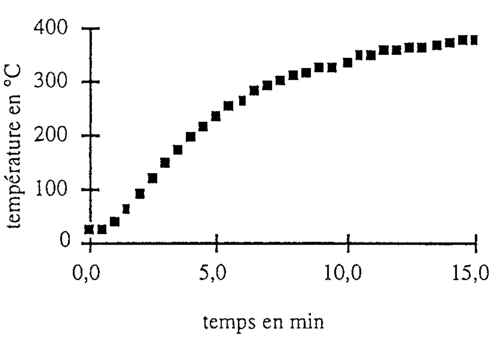


figure n°2

3.3 MATERIAUX

Les six matériaux sélectionnés sont représentatifs d'un aménagement de cabine d'avion.

matériaux représentatifs d'un coussin de siège:
- un tissu décor
composition : 96 % laine, 3,4 % nylon, masse volumique : 360 g/m^2
- une mousse polyuréthanne de densité 43
- un tissu barrière feu
composition : 70 % tissu préox, 30 % aramide

revêtement de sol
- une moquette
composition : laine marron à chevrons noir sur support jute et coton/latex ignifugé

rideaux
- un tissu polyester
composition : 100 % polyester

isolation
- une enveloppe de matelas
composition : tissu de verre imprégné d'hypalon ivoire (hypalon : polyethylène chlorosulfoné).

3.4 CRITERES ETUDIES

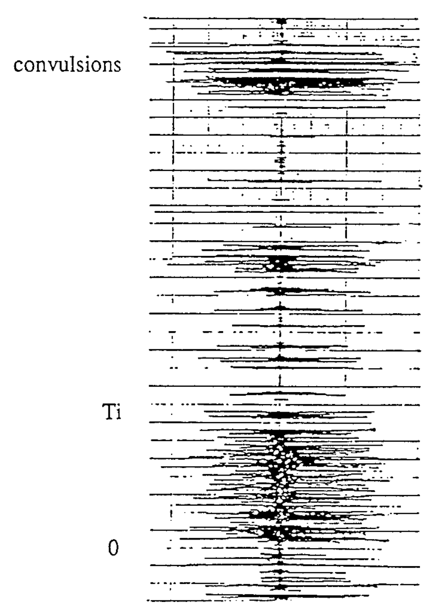
Perte de masse notée Δm

La perte de masse a été enregistrée toutes les trente secondes pendant les 15 minutes d'essai. Le critère retenu est la perte de masse au temps d'apparition de l'incapacitation.

Temps d'incapacitation noté Ti

Définition : après une période d'activité normale durant laquelle l'animal explore la cage, on constate une phase de diminution d'activité. Durant cette phase, l'animal reste immobile plusieurs dizaines de secondes avant de reprendre une activité exploratoire accrue pour tenter d'échapper aux effluents toxiques. C'est le délai au bout duquel une première modification nette de l'activité des animaux est observée qui a été choisi comme critère.

Un exemple de l'activité des animaux soumis aux effluents gazeux issus de la thermolyse de la mousse polyuréthanne est donné ci-aprés:



4. RESULTATS

matériau	masse initiale	Ti min	Δm (g) au Ti	Δm total (%)	Δm valeurs réduites
laine	6,4	3,8	1,34	64,0	0,981
	6,4	3,8	1,24	65,0	0,996
	8,0	3,6	1,01	63,0	0,966
	8,0	3,5	1,19	64,9	0,995
	8,0	3,5	1,03	66,4	1,018
	12,0	3,5	1,35	66,4	1,018
	12,0	4,0	1,47	67,0	1,027
mousse PU	5,4	3,6	0,80	96,4	1,031
	5,4	4,1	0,97	-	-
	5,4	3,8	0,91	96,2	1,029
	5,4	3,8	0,95	92,0	0,984
	5,4	3,7	0,85	96,0	1,027
	5,4	3,8	0,85	90,1	0,964
	5,4	4,3	0,94	95,6	1,023
	8,4	3,0	0,78	92,2	0,987
	8,4	3,5	1,18	92,5	0,990
	8,4	3,2	1,45	91,6	0,980
	10,1	3,2	1,06	92,0	0,984
env. matelas	5,1	4,7	0,93	65,0	1,016
	5,1	7,6	0,91	66,2	1,034
	5,1	4,5	0,87	66,8	1,044
	10,0	4,9	1,38	65,9	1,030
	10,0	5,0	1,15	59,2	0,925
	10,0	5,0	1,03	59,4	0,928
	10,0	5,0	1,40	73,0	1,141
	15,0	3,9	0,64	64,6	1,010
	15,0	3,9	0,74	60,8	0,950
	15,0	4,3	0,88	58,9	0,921
tissu FBL	5,4	6,0	1,01	35,5	1,141
	5,4	6,1	0,95	30,1	0,967
	5,4	6,1	0,99	28,0	0,900
	8,2	5,5	1,13	22,5	0,723
	8,2	6,1	1,16	38,7	1,243
	8,2	5,0	1,12	30,3	0,973
	10,3	6,0	1,46	32,8	1,054
	10,3	5,5	1,50	31,1	0,999
tissu polyester	5	10,2	0,93	64	0,928
	5	9,8	0,78	74	1,072
moquette	5,5	4,8	0,77	70,7	1,103
	5,5	5,3	0,81	69,0	1,077
	5,5	5,8	1,10	67,3	1,050
	5,5	5,6	0,94	58,4	0,911
	10,2	4,3	1,04	68,6	1,071
	10,2	4,4	1,18	62,5	0,975
	10,2	4,0	0,98	61,7	0,963
	15,0	3,5	0,90	58,7	0,916
	15,0	3,8	1,06	59,8	0,933

tableau n°I

L'exploitation des résultats est réalisée sur les pertes de masse des six matériaux précités. Le tableau n°I regroupe les résultats d'essais sur 47 échantillons :

- les pertes de masse Δm au temps Ti
- les pertes de masse totales, Δm total, en pourcentage sur la durée de l'essai.

4.1 VALIDATION DE MONTAGE

Afin de valider le montage un test d'ajustement graphique, la droite de HENRY, a été réalisé. Le principe de ce test consiste à s'assurer qu'après avoir choisi un modèle connu de répartition des données, dans notre cas l'ajustement à une loi normale, l'écart entre le modèle théorique donc les valeurs théoriques calculées et les valeurs expérimentales, soit acceptable.

Le test est établi sur la population suivante :
Rapport exprimé en % de la perte de masse totale de chaque échantillon sur la moyenne par classe soit : $\dfrac{\Delta mi\ (\%)}{\overline{\Delta m}\ (\%)}$, la classe correspond à chaque famille de matériau.

droite de HENRY : pertes de masse

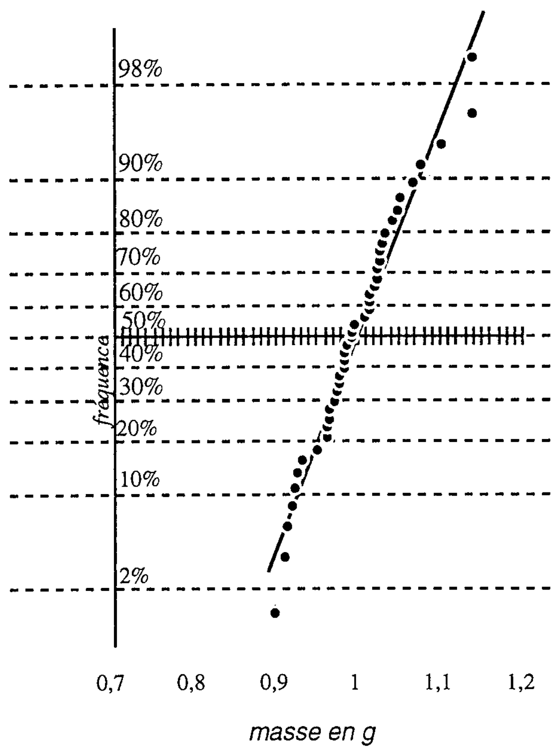
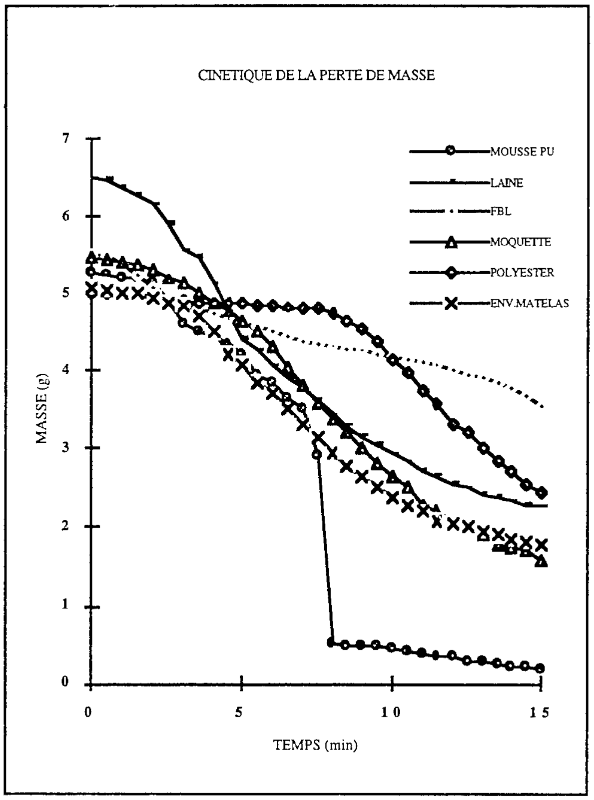


figure n°3

Toutes classes de matériaux confondues sur quarante quatre individus l'hypothèse de normalité est vérifiée avec un coefficient de corrélation de 95 % (intervalle de confiance sur la moyenne P = 95 %). Les valeurs expérimentales obtenues avec cet équipement suivent une loi normale et peuvent être acceptées et le montage ainsi validé.

5. RELATION PERTE DE MASSE - INCAPACITATION



DELAI D'APPARITION DU Ti (min)	
mousse PU	3,9
laine	4,2
tissus FBL	6,1
moquette	5,4
polyester	10
enveloppe de matelas	4,6

figure n°4

La diversité des cinétiques de combustion est illustrée sur la figure n°4. Certains matériaux ont un comportement comparable (moquette, polyester, enveloppe de matelas), par contre le tissu barrière feu présente comme attendu une faible dégradation. Pour la mousse polyuréthanne, il apparaît une inflammation spontanée vers 8 minutes, quelle que soit la masse de matériau engagé, et on peut constater que les premiers signes de l'incapacitation se produisent autour de 4 minutes ce qui confirme l'intérêt d'étudier les effets toxiques des effluents gazeux dès l'apparition de ce phénomène.

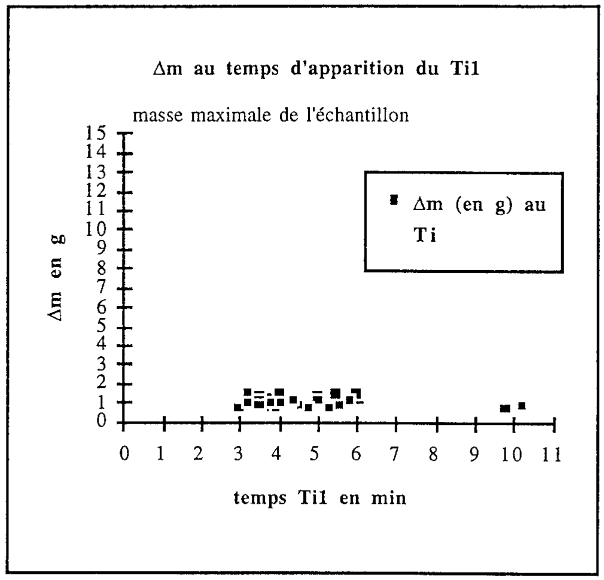
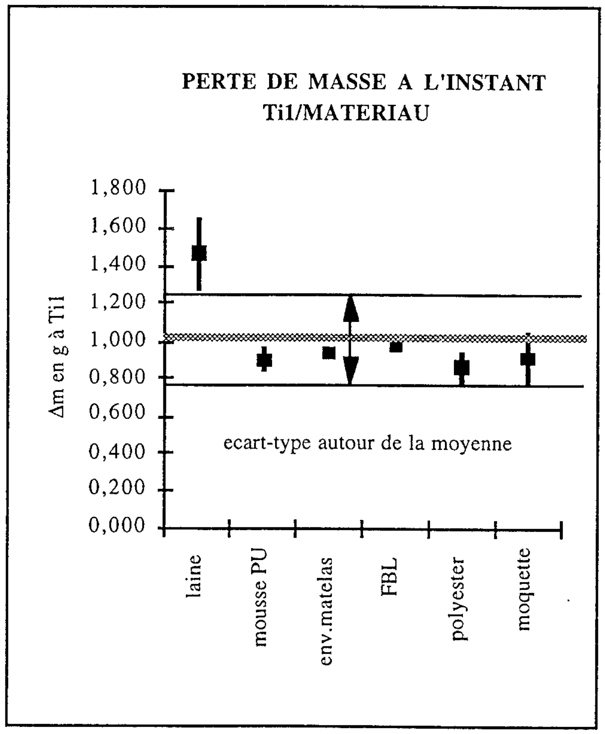


figure n°5



moyenne générale	1,009
écart-type	0,233
coef. de variation	23,1%
moyenne - écart type	0,776
moyenne + écart type	1,242

figure n°6

La figure n°5 donne la représentation de la perte de masse des matériaux à l'instant Ti. Globalement on constate que l'incapacitation des animaux se produit lorsque 1 g de matière est passé à l'état d'effluent gazeux. Il faut donc une certaine concentration de toxiques cumulée dans les voies respiratoires pour que le seuil d'alerte soit atteint, quelle que soit cette matière. Bien entendu, la valeur de 1g est directement liée au modèle feu utilisé. Cela signifie que malgré des cinétiques très différentes, des corrélations apparaissent entre temps d'incapacitation Ti et quantité de matériau dégradé thermiquement. Afin d'affiner cette analyse, les résultats sont examinés par classe de matériaux et par groupe de masses identiques. Le graphe de la figure n°6 présente les résultats obtenus sur vingt trois données pour des masses autour de 5 à 6g. On constate que pour la laine les valeurs s'écartent de la moyenne toutes classes confondues. Ce résultat s'explique car le montage d'essai a été modifié pendant l'évaluation de la laine afin d'améliorer l'ensemble de la chaîne de mesure. Les dispersions obtenues sont tout à fait acceptables dès lors qu'elles touchent des mesures biologiques. En effet les paramètres liés directement au comportement animal (adaptabilité, stress) limitent de manière importante la répétabilité des mesures. Quant à la précision de l'enregistrement des pertes de masse (1 mesure toutes les 30 secondes), elle est suffisante pour mettre en évidence la relation liant Ti à la valeur critique de perte de masse.

6. INTERACTIONS ENTRE TOXIQUES MAJEURS

Sachant que le CO n'est pas le seul toxique responsable des phénomènes biologiques, l'approche du risque global incendie des matériaux impose de vérifier la nature des interactions éventuelles entre toxiques dits majeurs.

Nous avons sélectionné (excepté l'HCN pour des raisons de sécurité) les toxiques majeurs rencontrés généralement dans les effluents gazeux dégagés au cours d'incendies de matériaux. Les effets des combinaisons des gaz purs ont été mesurés à partir de la concentration létale notée CL50 qui est la concentration nécessaire pour atteindre la mortalité de la moitié des animaux exposés en un temps donné. C'est aussi le paramètre couramment utilisé pour l'appréciation de ces effets. En effet, les gaz de combustion agissent sur l'organisme sans provoquer nécessairement l'incapacitation. Ils sont traditionellement classés en deux familles : les narcotiques et les irritants.

CO : narcotique
CO2 : narcotique
NO2 : irritant à effet narcotique
SO2 : irritant
HCl : irritant
Acroléine (CH2=CH-CHO) : irritant

Des mélanges complexes à 2, 3, 4 et 5 gaz ont été réalisés à partir des CL50% mesurées sur gaz purs. Les concentrations létales ont été déterminées pour tous les gaz étudiés pour une exposition de 15 minutes sur 5 souris blanches de race SWISS de 20g chacune et sont regroupées dans le tableau suivant :

GAZ	CL50% (ppm)
CO2	325000
CO	4800
HCl	10000
SO2	2550
NO2	690
Acroléine	215

tableau n°II

Pour l'exploitation des résultats sur les mélanges, (tableau n°III) les concentrations des différents composés sont données en pourcentage ou en fraction de la CL50 du composé seul. Une méthode simple d'évaluation a été développée. Elle repose sur le principe suivant :

dans un mélange à deux gaz où C'1 est la concentration du composé 1 et égale à la CL50/2 du composé 1, on cherche alors la concentration C'2 du composé 2 provoquant la CL50 du mélange. Ainsi les interactions entre les gaz peuvent se traduire par :

$$\sum \frac{C_i'}{C_i} = 1 \quad \text{====>} \quad \text{effet additif}$$

$$\sum \frac{C_i'}{C_i} < 1 \quad \text{====>} \quad \text{effet de synergie}$$

$$\sum \frac{C_i'}{C_i} > 1 \quad \text{====>} \quad \text{effet d'antagonisme}$$

La formulation a été généralisée et met en évidence l'écart au 1 théorique de l'additivité des effets. Cet écart est formalisé par un terme produit qui est l'expression générale d'une interaction :

$$\sum_i \frac{C_i'}{C_i} + \alpha\pi \frac{C_i'}{C_i} = 1$$

avec α : coefficient d'interaction

<u>domaine d'utilisation</u> : le calcul de α est exploité lorsque la CL50 du mélange est atteinte.

- Si α évolue entre -0,5 et +0,5 la tendance n'est pas marquée.

- Pour les mélanges à plus de 2 gaz, le terme "produit" des fractions de gaz dans le mélange est remplacé par la somme des termes "produit" pris deux à deux.

Le tableau ci-après regroupe quelques résultats obtenus sur mélanges réalisés à partir des fractions des CL50 sur gaz purs :

MELANGES	% TOTAL	MORTS	COEFF α	EFFET
BINAIRES				
CO 2800ppm CO2 15%	104	2/5	-0,15	additivité
CO 1550ppm NO2 530ppm	109	3/5	-0,28	additivité
SO2 1800ppm NO2 270ppm	110	1/5	-0,35	additivité
CO 2000ppm Acroléine 130 ppm	112	3/5	-0,4	additivité
CO2 7,2% SO2 1000ppm	61	3/5	+4,54	synergie liée au CO2
TERNAIRE				
CO 1750ppm CO2 7,3% Acroléine 60ppm	87	2/5	+0,53	synergie liée au CO2
QUATERNAIRES				
CO 1100ppm CO2 7,3% SO2 749ppm NO2 270ppm	113	3/5	-0,28	additivité
5 GAZ				
HCl 4450ppm NO2 100ppm CO 700ppm CO2 6,8% SO2 400ppm	110	2/5	-0,23	additivité

tableau n°III

Lorsqu'il y a mélange de gaz binaire, ternaire ou quaternaire, l'addition d'action a été observée en règle générale malgré la complexité analytique des mélanges réalisés. Il n'a pas été remarqué d'antagonismes notables. Par contre un phénomène de synergie indiscutable est observé lorsque les concentrations en CO_2 se situent entre 5 et 8% en volume. L'excitation du centre respiratoire bulbaire des animaux provoque des hyperventilations augmentant la prise de toxique par voie aérienne et aggravant de façon importante les intoxications.

7. CONCLUSION

En fonction de tous ces résultats, il apparaît qu'au niveau du laboratoire, plusieurs données importantes sur la toxicité des produits de thermolyse des matériaux peuvent être acquises. En se basant sur l'effet d'incapacitation des animaux, dans les conditions imposées dans notre laboratoire, (four "MINI CORNER TEST"), une relation entre la perte de masse des échantillons et l'incapacitation des animaux a été mise en évidence. Le phénomène le plus remarquable est que l'incapacitation apparaît toujours lorsque 1 gramme de matériau a été dégradé. La notion de gramme est évidemment reliée aux conditions opératoires, en particulier le volume de l'enceinte et son renouvellement (ventilation). Des constantes de même nature doivent être retrouvées, fonctions de la géométrie et de la dynamique des systèmes mis en œuvre. L'essentiel de la perte de masse est bien entendu lié à l'émission de CO et CO_2. L'étude des interactions entre les différents gaz majeurs ne conduit qu'à des additions sauf pour le CO_2 qui potentialise nettement l'effet du CO. Il n'est donc peut être pas étonnant de voir que ces deux gaz, majoritaires dans les produits de combustion, provoquent des effets toxiques liés étroitement à la perte de masse. Cette donnée pourrait donc constituer une voie indirecte d'évaluation de la toxicité potentielle des matériaux.

Il resterait alors à préciser un critère de sélection des matériaux qui pourrait être:

-soit le temps auquel le débit massique est maximum

-soit un pourcentage limite de perte de masse à un temps donné.

Afin de vérifier la validité de cette hypothèse, le CEAT envisage d'étendre les essais à un éventail plus large de matériaux d'aménagement de cabine.

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DISCUSSION - PAPER NO. 28

D. Dierdorf (Question)

Some inert gas Halon replacements intentionally add CO_2 to increase the respiration rate and prevent hypoxia. Would you feel that this would create a synergy or antisynergy with toxic gases?

A. Mansuet - Author/Speaker (Response - Translated)

CO_2 has a synergy effect. When combined with other gases, it reaches concentrations of between 5% and 8% by volume; for higher quantities, the phenomenon of hyperventilation is replaced by an inhibition effect.

I think that the addition of CO_2 is dangerous because of the high number of possible combinations with the other gases released in a cabin fire. In such cases, the scenario is not controlled. The risk for passengers located near the extinguishment zone is too high compared to the theoretical reduction in the risk of hypoxia.

F.S. Knox (Question)

Why did you not show HCN as a product of interest?

A. Mansuet - Author/Speaker (Response)

I didn't speak about HCN toxicity because, in this study conducted at CEAT, HCN was not used for safety reasons (the handling of HCN pressurized bottles is too dangerous). However, it is true that the amount of HCN released during a fire depends on several factors (ventilation, temperature, ...) and even if the rate of HCN is low, the level of toxicity remains high. As a reminder: the CL 50% on mice with an exposuretime of 15 minutes is about 230 ppm.

CAUSE OF DEATH - FIRE OR TRAUMA?

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1. INTRODUCTION

Differentiating between competing possibilities is often a difficult task. When fire is involved the problems are so much greater because of the combustion of evidence and the capacity for mimicry. It is not unknown for finite answers to evade even the most cautious scrutiny and thus the answers to right and proper questions must, in medico-legal language, be considered to be unascertained.

In an aircraft accident, where much may depend upon the availability of precise information, this capacity for failure is troubling, as indeed it is in many other situations. However, because of the publicity which may accompany a fatal aircraft accident, with demands for changes in design, this is an impediment which causes great concern.

Superficially it may seem that there ought not to be any difficulty, but this is to ignore the nature of fires. Moreover, it assumes that there are always clear indications of the cause and manner of death, and that the diagnostic difficulties are entirely a product of a failure to observe the signs. This is clearly not the case, though it has to be acknowledged that if the investigation is lacking, then there may not be enough evidence to make a proper diagnosis.

This paper looks at these difficulties and places them in the context of the search for improved flight safety.

2. THE MANNER AND CAUSE OF DEATH

It is important that the difference between the way someone dies and what they die from is understood. At its simplest someone may be in heart failure when they die, but this only tells part of the story. We have to know why that person developed heart failure, if we are to be able to prevent future occurrences. Thus the person's heart may have failed because they had ischaemic heart disease or some other disease of the cardiovascular system.

In fires the demarcation is not so clear cut. Usually people are said to have died because they suffered burns or they inhaled the products of combustion.

Where people die immediately or whilst the fire is raging this classification may be straight forward. Some may survive only to die later because they developed some complication either of the burns or the smoke inhalation.

Anyone who has ever been burnt or who has inhaled smoke may develop shock. This is a term which is often loosely used. Essentially it means that there has been an acute circulatory failure and that has led to generalised tissue hypoxia. The mechanisms involved are complex and not fully understood. They may be summarised by saying that there are widespread responses, which are mounted to deal with noxious stimuli. These can cause inadequate perfusion of the tissues because of changes in the microcirculation. This is a particularly serious problem which may be seen in the victims of fires. It can lead to the failure of a range of organs, the so-called multi-organ failure. Usually people who develop this have serious sepsis. Those who have been burnt or who have developed pulmonary smoke inhalation injury are particularly prone to sepsis.

Lung injury is associated with oro-facial burns and smoke inhalation, the mechanisms and causes of which have been well discussed in the literature (1,2,3,4,5). This may lead to the adult respiratory distress syndrome; the basic features of which are outlined in Table 1.

Severe Dyspnoea
Tachypnoea
Refractory Cyanosis
Loss of Lung Compliance
Diffuse Alveolar Infiltrates

Table 1. - Basic Features of ARDS

There are many causes of this very severe complication which carries a high mortality. Even when uncomplicated, some 40% of patients will die and where there are added factors such as increased age and failure of other organs, then the death toll is even higher. In so far as fire victims are concerned, there may be many complicating factors, such as heat damage to the upper respiratory tract and chemical damage to the lungs. These are easily understood and to some degree their role in the pathogenesis of ARDS may be said to be expected. However, it may be that there is an added factor, which might not be easily recognised, unless it is looked for. Fat embolism and other trauma may predispose to its development. Normally it would be expected that mechanical trauma sufficient to cause the release of fat into the circulation would be diagnosed. However, decompression sickness may cause this problem. Thus it could theoretically happen if an aircraft decompresses rapidly and is involved in a fire. Obviously this would be a most unusual circumstance, but it illustrates the fact that a wide ranging audit of the causes and mechanisms of responses to fires has to be undertaken. It also illustrates some features of the complexity of the diagnostic problems found in this situation.

The other aspect of the way and how people die in fires relates to the possibility of intercurrent mechanical trauma. Here the problems are those of diagnosis and the extent to which they may be responsible for the death.

In highly destructive accidents, the diagnostic difficulties may not be great because these are high, abrupt decelerations, accompanied by considerable structural damage. Nevertheless, the pathologist must always be aware of the possibility that not all of the injuries seen are in fact the result of mechanical

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trauma.

To understand why this is so and how it can happen, we need to look at the way in which heat affects the body.

Heat intensity and survival are inextricably linked to one another, as is injury causation, which can have profound effects upon differential diagnosis. One of the most important influences affecting escape is the fact that heat causes pain. This is by definition a subjective phenomenon, individual response to it being highly variable (6). Although the lower threshold for pain is a fairly constant phenomenon for an individual, tolerance is a vastly different matter. It represents the upper threshold limit, being the maximum amount of heat to which that person will willingly allow themselves to be exposed. The actual level can be manipulated by drugs and it is markedly affected by psychological factors, unlike the pain threshold. The latter is very much dependent upon the method of measurement used (7). Pain thresholds may be altered by various diseases. Wernicke's encephalopathy, for example, can raise the threshold, but this must not be confused with pathological desires to suffer pain, which may be seen in mentally subnormal individuals (8).

A bath at body temperature is usually quite acceptable, but if the temperature is raised by 5-8°C, to 42-45°C, then it becomes unbearable. Most observers feel that the pain threshold to heat lies somewhere within the region of 45°C. Rectal temperatures of 42-45°C in pigs seem to be critical for the onset of systemic hyperthermia. Once 44°C is reached, the animal will only survive for a few minutes. Some individual variation in physiological responses has been recorded. Generally though, the blood pressure rises at first and then it falls. The same is usually true of the respiratory rate, but electrocardiographic changes are less consistent (9,10).

A skin temperature of 44°C can be tolerated for six hours before it burns. Thereafter, for each degree rise in skin temperature between 44°C and 51°C, the time taken to produce burning is halved. A skin temperature of 70°C can only be tolerated for less than one second.

Tolerable exposure times for ambient temperatures are quite different. Thus 90°C may be tolerated for as long as 45 minutes without causing burning. However, 108°C will produce irreversible cutaneous injury in only 30 seconds. Loss of consciousness and death can occur after a few minutes of exposure to 100°C (9,10,11).

Tolerances to higher temperatures have been studied but it is unlikely that any knowledge of them could ever really be of value in terms of preventative design (12).

It would seem, from the information available, that heat causes a hyperthermic circulatory collapse which may be of two distinct types. At temperatures below 200°C this seems to be peripheral in origin and is characterised by a longer exposure period. Centrally initiated collapse is precipitated by brief exposures to high temperatures.

In an unventilated room a gasoline fire will produce a temperature of over 800°C at the ceiling in just a few seconds. If ventilation is added then temperatures approximating to 1000°C may be reached in ten seconds (9). It is not inconceivable that, with the same materials, aircraft could produce the same temperatures.

Now when animals as large as pigs and dogs are put into a room, in which the temperature reaches from 500 - 1000°C for a period of 30 seconds, some will die almost immediately. Post-mortem examinations on the animals which have died thus do not reveal any evidence of death due to asphyxia, carbon monoxide poisoning or the inhalation of flames. Rather death is due to a systemic disturbance. Such a condition can arise even in the absence of any significant amount of cutaneous heat injury.

The most consistent autopsy findings are widespread visceral ecchymoses. These are particularly prominent in the subendocardium of the cardiac ventricles. The latter are usually contracted. In those animals which do not inhale hot air, the only evidence of broncho-pulmonary injury is the finding of some pulmonary oedema. Animals which survived for a period and are later sacrificed are usually found to have adrenal cortical necrosis.

Heat may also be transmitted to the victim by convection. Much less work has been done on this topic compared with that on radiant sources. It would seem from the available evidence that severe patho-physiological disturbances can occur at much lower temperatures.

Early studies of the victims of fires revealed that they frequently sustained pulmonary injuries and that these were of equal, or greater importance to survival than are skin burns (13). Three major patterns of injury were recorded. Firstly, damage was largely restricted to the upper airways, with little or no actual lung injury. In other cases profound pulmonary damage was seen, with comparatively little upper airway injury. Finally, the entire respiratory tract was affected.

This and other studies have helped to define the important morbid anatomical findings in deaths due to burning. Unfortunately by the time that the body is extricated, there may have been considerable incineration of the body, thus changing the appearances from those which were present at the moment of death. These artefacts can make it very difficult to differentiate between ante, cum and post-mortem injuries. Many instances have been recorded in which the three have been misinterpreted, so that violence has been missed and erroneously attributed. The characteristic pugilistic attitude seen in incineration, which results from the greater strength of the flexor muscles compared with the extensors, has and presumably will be regarded as evidence of self-protection. Skin-splitting, non-thermal skin blistering due to kerosene, carbon monoxide and drugs have similarly been misinterpreted (14,15).

Hair colour may change in a hot environment. At 250°C grey hair becomes a brassy blonde colour and a slight reddish tinge may be seen in brown hair heated to 400°C. Black hair does not change colour.

As heat dries the body all of the tissues may shrink. Up to 60% of the total body weight may be lost. If this is combined with the characteristic flexion contracture, then reductions in stature of many centimetres may be seen. This all contrives to give a totally false idea of the victim's stature. If this is used as evidence of identity then it may deceive.

One of the most difficult problems to overcome is the differentiation of the thermal and physical trauma in the pathogenesis of fractures. These are such a common finding in fatal aircraft accidents that it is tempting to assume that all those seen are due to impact injury. It is almost understandable that someone could opine that a fracture was produced by impact

and that its typical appearances were a result of post-mortem incineration. Many burn fractures have a 'flaky' appearance and the absence of associated soft tissue injury should assist in making the differentiation.

One of the most disturbing findings in fires, which can cause considerable difficulty in differentiation, is heat fracture of the skull. Burning of the scalp and the outer table of the bone reduces the strength of the skull. The heat vaporises the fluid within and around the brain, which generates pressure, ultimately producing the typical 'blow-out' fracture seen in fire victims. A shrunken brain, the absence of soft tissue trauma and depressed fragments should differentiate heat and impact fractures. Artefactual haematomata, due to the rupture of blood vessels, may further complicate the picture. These are usually bilateral as opposed to traumatic subdural haemorrhage, which is characteristically unilateral.

Typically soot in the mouth and the upper respiratory tract is regarded as a sign of existence during the fire. This finding should be viewed with caution, because it could be agonal. It is always best to correlate these appearances with the histological findings of an acute inflammatory response. However, to complicate matters further this may not have time to develop. The presence of copious mucous indicates life during the fire, even in the absence of any carboxyhaemoglobin.

3. DISCUSSION

Deaths in fires are often problematical, and resolving the difficulties posed is never easy. If full autopsy findings are not available, then it is not possible to give answers to many of the questions which may be raised. Indeed, in aircraft accidents it could be highly dangerous to attempt to answer them because false information may be instrumental in producing design changes which do not confer the safety benefits claimed for them. Even when circumstances seem to dictate that those involved could only have died in a particular way, if the evidence is not elicited, then the causes of death cannot be ascribed.

To a large degree there are three ways in which people may die in a fire, from the inhalation of the products of combustion, from trauma or from heat. Unfortunately, combinations do occur and it is the disentanglement of these which medico-legally, and from the point of view of safety design, are so important. The toxicological findings in any one instance, may not indicate anything more than the fact that there was survival for a time. this could occur even in someone who had potentially fatal injuries. Thus a judgement has to be made would that person have survived if there had not been a fire, even if only for a short time? If they had done so, were their injuries a consequence of flawed design or non-survivable impact forces? There are no easy answers, and each case has to be considered on its own merits, irrespective of the remainder of the population.

Usually in the absence of trauma, toxicological evidence gives a clear cause of death but, there may be instances where complications, such as ARDS arise. Whilst these could be said to be foreseeable, they are not necessarily inevitable and it is possible that by changing a cabin material or some other feature, the toxic insult could be lessened and the chances of survival enhanced.

Borderline cases are diagnostically the most problematical and give rise to the sharpest debates. In the absence of any mechanical injury, and where there are equivocal toxicological results, then the part played by heat stress has to be debated. This is a very real possibility, especially when the fire is in an enclosed space and there is a rapid rise in temperature.

It can be seen from the foregoing, that dealing with the victims of fires is not straightforward. The ability of heat to produce haematomata and fractures simulating trauma has caused misinterpretations even by those who were wary. It follows therefore, that each and every case must be carefully analysed, the findings being considered in the light of the circumstances. Often there will be little information available, thus denaturation of tissues by heat may make them histologically useless and so signs of trauma may not be evident under the microscope.

In the face of such difficulties all that can be reasonably expected, is that the pathologist examines the evidence fully and carefully. Thereafter, if there are doubts, then these must be expressed. Moreover, in all cases only cautious inferences should be drawn and, if necessary, these should always be reviewed if further information is forth-coming.

4. CONCLUSIONS

This paper taken a broad look at the basic problems involved in diagnosing the cause of death in fires. It has emphasised the difficulties which may be encountered and advised caution in interpretation. Flight safety will not be served by hastily considered conclusions, which do not withstand audit.

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DISCUSSION - PAPER NO. 30

J. Andrews (Question)

Is it possible to establish reliable data on subsequent death or illness due to the long term effect of the ingestion or inhalation of toxic smoke?

I.R. Hill - Author/Speaker (Response)

Yes it is possible, but may not be entirely practicable, because of the range of factors involved and the relative lack of reliable data. A lot of work has been done on fire-fighters; this showed that they did not have an increased incidence of malignant disease of the lung when connected to working habits. However, the issue of chronic lung disease is not so easily explained. There is evidence to suggest that following smoke inhalation injury, there can be decrements in lung function and that these may be progressive. What we really need is long term follow-up of people who have been exposed to smoke and have sustained injury due to it.

E.R. Galea (Comment/Question)

I have a comment and a question:

Comment: A considerable amount of temperature tolerance data is poorly documented and reported. Temperature tolerance is not simply based on air temperature alone but on, for example: (a) physical state of the subject, (b) level of activity during exposure, (c) amount of clothing and, most importantly, (d) amount of water vapour in the air, i.e. humidity. The last point is quite important as water vapour has a higher heat capacity than dry air, and so delivers a greater amount of heat to the subject than dry air, and water deposited on the skin changes the conductivity of the skin.

Question: In your Paper, you refer to pig data, particularly tenability limits. How relevant is this raw data to humans, given that pigs have different mechanisms from humans for dealing with heat, e.g.: (1) pigs do not perspire (in humans this is a cooling mechanism), (2) perspiration on the skin changes the thermal conductivity of the skin, etc..?

I.R. Hill - Author/Speaker (Response)

I do not accept that the data is poorly documented; there is a wide range of publications dealing with this topic. It is an inevitable consequence of biological diversity that in a range of differing circumstances, a variety of responses will be evoked. Moreover, an individual's responses to stimuli will vary from day to day. Inevitably this causes considerable difficulties for those who have to express an opinion about the consequences of exposure to various stimuli, and it is why so many of these opinions are couched in cautions terms. Obviously, and especially in circumstances where harm may accrue, it is not possible to carry out a full range of tests on human beings. Thus animal surrogates have been used. Of course these can only give approximations, but they are superior to many other techniques, because they mount pathophysiological reactions which can be monitored. The latter are of considerable importance to survivability. As a general rule, it is advisable to take lower tolerance values as a guidance. Any other approach may reduce the value of any safety proposal.

F.S. Knox (Question)

Could you address relative susceptibility of passengers by age or health status? It should be factored into cost-benefit considerations.

I.R. Hill - Author/Speaker (Response)

The age and general health of people has a marked effect upon the ability of people to whitstand fires. Thus, someone with severe cardiovascular disease will be more susceptible to increases in the carbon monoxide content of the atmosphere than someone who is fit and well. Similarly, those with severe respiratory disease, who are already biochemically compromised, will more easily succumb. Also, the infirm will physically find escape more difficult.

Insofar as cost-benefit calculations are concerned, clearly aircraft design has to take into account the fact that passengers are selected by their ability to pay the fare, and not according to their physical and mental health. In any passenger complement, there will be people with a variety of disabilities, who will find escape difficult. Obviously, this is not an easily resolved situation, and inevitably there will be compromise; whenever possible, people with disabilities should let airlines know. I suspect that many do not.

Toxicity Issues in Aircraft Fire Science

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1. ABSTRACT

Many factors must be considered when using experimentally derived toxicity information to predict human response. Two important principles for appropriate use of toxicity data include obtaining information from an appropriate source and applying that information appropriately. Examples from our laboratory research are included, in which bench-scale combustion tests of advanced composite materials were conducted, collecting information such as mass loss rate, particle characteristics, and chemical characteristics of the smoke. Methods we employed in the evaluation of ACM combustion products include: (a) chemical analysis of the vapor and soot, (b) continuous plume temperature recording, © continuous monitoring of combustion gasses, (d) determination of mass loss rate during combustion, and (e) morphologic evaluation of airborne particulate matter using light and electron microscopy, combined with computer-based image analysis.

2. OBTAINING TOXICITY INFORMATION

Toxicity information is available from many sources. An epidemiologist or medical examiner is able to gather substantial information from treatment records following a fire scenario or from post-crash investigations and autopsy. Epidemiological data are valued because they represent an accurate illustration of human physiological response in a fire. It is difficult to make predictions from this information, however, or apply it to another scenario because very little is known of the actual exposure conditions, the physiological state of the victim, or the amount of material cleared from the body. Autopsy can provide chemical analyses which show the dose delivered to the tissue, but obtaining relevant biochemical information is not always possible.

Recent developments in automated data acquisition and advanced instrumentation, coupled with computer manipulation of the data, can produce a very accurate picture of the physical processes occurring in a fire, resulting in more accurate biological simulations, better predictions of physiological response, and enhanced modeling of human behavior. These technological advances can be well illustrated by comparing the current relationship between bench-scale and full-scale material testing. A comprehensive chemical and physical analysis of the smoke produced in each scenario reveals some commonality, yet quantitatively, the two are quite different. Bench-scale tests provide extensive information about the smoke concentration generated from burning materials and are easily modifiable, but these conditions only approximate an actual fire. The strength of bench-scale combustion research is the ability to precisely control the environmental scenario, accurately measure the outcome, and reliably duplicate test conditions while exploring the biological effects of exposure.

Data obtained from full-scale test facilities are invaluable for "real world" relevance, but these facilities are very expensive to establish and place high demands on personnel and equipment resources. They are also not well suited to the collection of physiological data because the experimental conditions are difficult to control and reproduce. By integrating the specific strengths of each method through computer analysis and mathematical modeling, though, a substantial portion of the puzzle can be assembled. The physical properties and chemical nature of smokes produced in a bench-scale furnace and in a large-scale test facility have been well characterized. As analytical capabilities improve and modeling technologies are applied, comparisons of the atmosphere's physical and chemical properties become more complete. Physiological relationships between the laboratory animal and the human can be mathematically described. The exposure of an appropriate animal species to bench-scale combustion products and careful monitoring of a representative physiological response yields data used in the construction of an animal model of toxicity. That information is then used to construct a resilient mathematical model capable of describing the animal response to a controlled atmosphere as well as predicting the physiological effects an actual aircraft fire would have on a human. Mathematical modeling of these physiological response relationships between humans and laboratory animal species form the final link between laboratory scale toxicity testing and "real world" risk assessments.

While these mathematical descriptions are very good, it is important to recognize the extent to which the physiological and behavioral response of a laboratory animal is not necessarily indicative of humans, just as a cone-calorimeter does not accurately duplicate all aspects of an actual aircraft fire. This fundamental principle of toxicology is often overlooked by inappropriately applying toxicological data that are technically accurate, but only within a narrowly defined context. For example, the gas concentrations that are lethal to fifty percent of the exposed population (LC_{50}) for mice, rats, guinea pigs, and primates, are listed in Table 1.

Table 1: Approximate LC_{50} of three combustion gasses following a 30-minute exposure to carbon monoxide (CO), hydrogen cyanide (HCN), and hydrogen chloride (HCl). (Hartzell, *et al.*, 1988.)

Species	**CO** (ppm)	**HCN** (ppm)	**HCl** (ppm)
Mouse	3,500	170	2,600
Rat	5,000	120	3,800
Guinea Pig	17,500	200	1,350
Primate	3,200	200	5,000

Based on the information provided in Table 1, it is tempting to conclude that the guinea pig is a poor representative of CO poisoning in humans, while an adequate indicator of HCl toxicity. But this conclusion is misleading. The guinea pig is actually an excellent model of pulmonary toxicity in humans with respect to certain modes of action and physiological responses. The distinction between a dichotomous endpoint (lethality) and a graded response is significant to physiological modeling. As an endpoint,

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lethality is much less clear cut when making inter-species correlations than is a graded physiological response. Furthermore, it is inappropriate to consider lethality "The Index" of toxicity when lesser exposures may cause permanent debilitation, incapacitation or subsequent death from other factors. It is much more useful in predictive modeling to identify a measurable physiological parameter which corresponds to a graded toxicological response and is commensurate with degree of severity. The ability to establish a reliable link between exposure concentration and measured physiological response is critical to demonstrating a dose response and to the development of a predictive model of toxicity.

Historically, toxicity has been reported as the concentration of material in the breathing zone multiplied by the duration of the exposure (CT). To illustrate, Figure 1 shows a plot of hydrogen cyanide (HCN) lethality in humans, which is linear as displayed, but effects cannot be extrapolated beyond the acute response range.

An index of toxicity expressed as CT is linear only under special circumstances and with homogeneous atmospheres of limited complexity. There are numerous circumstances which make acute toxicity difficult to predict. An acute exposure to nitrogen dioxide (NO_2) and hydrogen fluoride (HF) gas, for example, may not cause death within twenty-four hours of exposure, but rather may evoke a

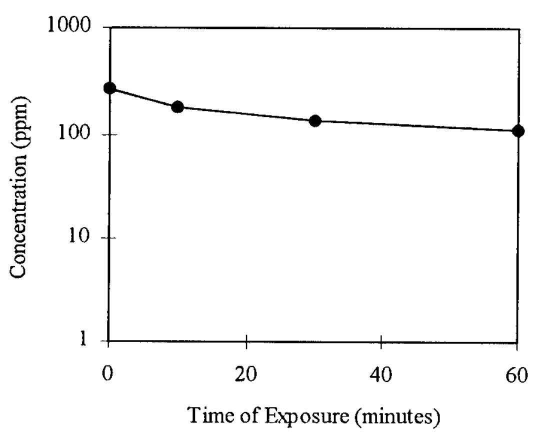

Figure 1: Lethality of hydrogen cyanide in humans.

biochemical response which initiates a chain of events leading to organ failure, system shut-down, and death several days later. Conversely, an animal with a compromised immune system or defective biochemical repair mechanism may die from a normally survivable toxic insult. The CT / response relationships are confounded by the chemical complexity of the atmosphere. For example, the time course to a given response for a fixed concentration (e.g., HCN) of an inhaled toxin may be altered by the presence of CO_2, which elicits a dosimetric elevation of breathing rate and thus more rapid uptake of HCN. Even the presence of water may be a confounding factor. The ocular, dermal, and respiratory hazard from exposure to acid gasses like HCl and HF will be substantially different in a moist environment such as would be produced by a water mist fire suppression system.

Incapacitation is a much more informative endpoint than animal death, especially if the goal is to establish a maximum safe concentration for human exposure. The concept of an incapacitating exposure is often used for regulatory purposes. The National Institute for Occupational Safety and Health defines the term, Immediately Dangerous to Life or Health (IDLH), to mean, "The maximum concentration from which, in the event of respirator failure, one could escape within 30 minutes without a respirator and without experiencing any escape-impairing (e.g., severe eye irritation) or irreversible health effects." (NIOSH, 1976) This illustrates an important aspect of escape models. While the primary route of entry in a fire scenario is pulmonary exposure, eye irritation may cause significantly higher pulmonary exposure if it degrades the ability of a crew member to locate an available exit and escape the burning aircraft. For example, a ten-minute exposure to 240ppm HCl is sufficient to produce incapacitation, but HCl is a severe eye irritant at only 5-10 ppm. (NIOSH, 1978) Algorithms describing the effective concentration necessary to cause incapacitation have been established and tested for several combustion gasses, but may not be sufficient for some situations.

Performance decrement measurements are another improvement to the usefulness of toxicity data. A refinement over incapacitation, the ability to measure performance decrement will now help military planners better predict whether a trained unit will complete a combat mission successfully, based on environmental factors such as previous exposure to hazardous materials and the overall health of the individuals in the unit.

Several methods are in use to assess performance in laboratory animals and are correlated to human behavior assessment. Exploratory behavior can be quantified and interpreted using a computerized tracking system, which reports such motion parameters as distance traveled or time spent ambulatory. (Forrest, et al., 1992) A sudden visual, auditory, or tactile stimulus can cause an unsuspecting animal to flinch. This startle response can be quantified, allowing statistical comparison of normal and compromised neurological function. Visual acuity and pattern recognition has been used as an index of neurotoxicity. Changes in nerve conduction velocity (Purser, 1984, 1992) or changes in respiration rate provide useful information about physiological status.

3. APPLYING TOXICITY INFORMATION

When reviewing analytical data for toxicological information, it is important to recognize that while important, findings are not necessarily all-inclusive with respect to potential toxicity. Table 2 presents a chemical analysis of the combustion products of three advanced composites. Information was collected in accordance with MIL-STD-2031(SH), *Fire and Toxicity Test Methods and Qualification Procedure for Composite Materials Systems Used in Hull, Machinery, and Structural Applications Inside Naval Submarines*, published in 1990 by NAVSEA.

Table 2: Comparison of three advanced composites: Analysis of gas evolved during combustion. (Sorathia, *et al.*, 1992, Sorathia and Forrest, 1992)

	CO (ppm)	CO_2 (%v)	HCN (ppm)	HCl (ppm)
GR/BMI	175	0.8	3	none
GR/BMI	10	trace	trace	1
GR/Epoxy	115	0.9	15	trace
GR/Epoxy	313	2.0	1	0.5
GR/Epoxy	160	0.5	2	1.5
GR/Epoxy	300	0.6	2	1
GR/PEEK	trace	trace	none	none

Based on the information provided in the table, it appears that a graphite reinforced (GR) composite with a polyether-ether-ketone (PEEK) matrix provides a slight toxicologic advantage over bismaleimide (BMI) or epoxy when burned. But this table only reports four gasses. As such, comparative risk assessments can be derived *only* with respect to these four materials in lieu of a direct assessment of toxicity. When composites are burned under less than ideal conditions, numerous organic materials are produced, many of which present a severe hazard. Studies in our laboratory, for example, demonstrated that over ninety compounds were generated from burning GR/BMI. With this many compounds present, toxic interactions between multiple chemicals in the smoke are likely to occur.

4. METHODS

Our laboratory developed and used a bench-scale combustion apparatus to evaluate the characteristics of smoke produced from controlled combustion of advanced composite material (ACM) consisting of a graphite-reinforced, chemically modified bismaleimide matrix (GR/BMI). Methods we employed include: a) chemical analysis of the vapor and soot, b) continuous plume temperature recording, c) continuous monitoring of combustion gasses, d) determination of mass loss rate during combustion, and e) evaluation of airborne particulate morphology and particle distribution using light and electron microscopy, combined with computer-based image analysis.

The primary goal of this phase of the study was to qualitatively evaluate the combustion products of GR/BMI. Soot was collected on a glass wool filter and the organic portion extracted with a mixture of 50% methylene chloride, 50% acetone; vapor was collected using cold-trap condensation. Both samples were analyzed in a Perkin Elmer 910 Gas Chromatograph/Mass Spectrometer (GC/MS).

The combustion chamber is a commercial version of the UPITT II cone calorimeter developed at the University of Pittsburgh (Caldwell and Alarie, 1991). It was subsequently modified through a US Army funded basic research project (Miller, et al., 1994) to permit control of heat flux and air flow, and to allow continuous measurement of mass loss during combustion. The apparatus consists of a conical-shaped hood containing a heating element (Fire Testing Technology Inc., West Sussex, UK) that will irradiate ACM samples (a 100mm x 100mm "coupon") at selected heat flux levels. Upon installation, a heat flux meter was used to correlate temperature with heat flux. Three flux levels were selected for our studies: 38.5, 57.2, and 84.2 kW/m^2, corresponding to 625, 770, and 880°C. A load cell is incorporated into the sample platform, allowing approximate measurement of mass loss during controlled combustion. The mass loss rate, expressed as grams of material released per minute of combustion (g/min), permits modeling of the resultant smoke plume.

Ventilation through the system is maintained by pulling unfiltered air through an access port located in the rear of the cone hood. Four ventilation rates were used, corresponding to 340, 370, 400, and 650 liters per minute (L/min). Smoke was vented from the combustion apparatus into a twelve-inch PVC duct 40' in length. Five sampling ports were installed at ten-foot intervals along the length of the tunnel to allow for direct sampling of the plume (Figure 1). Exhaust from the tunnel was pulled through a high efficiency particulate air filter and gas scrubber and vented into a laboratory hood. Gas sampling instruments (Rosemount Industries, Northbrook, IL) provided continuous monitoring of CO, CO_2, and O_2 in the exhaust during combustion. The digital output from these analyzers was collected in real time and stored on a PC equipped with a Keithley-Metrabyte data acquisition card. Thermocouples were placed at ten-foot intervals along the tunnel and positioned in the center of the air stream. Continuous monitoring was accomplished using a computer-based analog-to-digital data acquisition system.

We used several sampling techniques in an attempt to collect a representative sample of the aerosol generated during combustion. Methods employed included: a) multi-stage cascade impactors, b) single stage impactors, c) polycarbonate air filters, d) electrostatic precipitation, e) miniature cyclone deposition, and f) allowing the particles to settle out of the air stream onto aluminum scanning electron microscope (SEM) stubs and glass microscope slides placed on the floor of the tunnel.

A multi-jet, multi-stage cascade impactor fitted with a glass fiber filter in the final stage was used to determine the aerodynamic diameter of the aerosol particles evolved. Because smoke density was quite high close to the combustion chamber, trials showed that sampling devices located along the first section of the tunnel would rapidly become clogged. The first stage of a five-stage cyclone separator (Southern Research Institute, Birmingham, AL) was connected in series with the first impactor (located at section number one) to remove particles greater than 10µm from the sampling stream, preventing overloading of the first stage of the impactor. A Gilian high flow sampling pump (20 L/min) was used for the impactors; exhaust gas from the pump was routed back into the tunnel downstream of the sampling port with tygon tubing.

Single stage impactors (cutoff diameters less than 2.5µm or less than 10µm) and polycarbonate air filters were used on initial tests, but were found to be inadequate. Overloading of the intake jets with material would occur before an adequate volume of air could be sampled.

Cleaned aluminum scanning stubs prepared with an adhesive substrate were placed in a stainless steel holder and positioned on the floor of the tunnel at ten-foot intervals. Glass microscope slides

placed adjacent to the SEM stubs were also used as a collection surface for aerosol particles. A point-to-plane electrostatic precipitator (In-Tox Products, Model 02-1400, Albuquerque, NM) was connected to the tunnel near the furnace. This instrument was configured to collect aerosol particles onto polished carbon SEM planchettes or transmission electron microscope (TEM) grids. We found that carbon planchettes provided the most usable data; particle distribution on TEM grids was inconsistent. Particulate samples for evaluation by SEM were dried overnight in a vacuum desiccator, then sputter-coated with a 10-15nm layer of gold. Photomicrographs were taken of the surfaces using an Amray 1000B SEM at 20-30kV accelerating voltage.

Algorithms developed for particle analysis were employed using a Quantimet 570c (Leica, Inc., Deerfield, IL). Samples collected on glass microscope slides were magnified to 40x, 200x and 400x on a light microscope and the resulting images captured by a microscope-mounted CCD camera and digitized for image analysis. Photographs obtained by SEM were captured by a CCD camera mounted on a macro-(photo)stand. Particles were detected as "features" in each calibrated digitized image by comparing the gray level of the feature with the background gray level. The identified features were then measured using computer-based image analysis methodologies for area, perimeter and equivalent circle diameter.

5. RESULTS

Initial Characterization

Vapor and soot analysis of burned GR/BMI demonstrated that over ninety compounds were detected in each material. The primary organic groups identified in both the vapor and the soot were phenol and aniline. The eight primary components identified in the vapor (Table 4) account for over 90% of the volatile materials. Organic material extracted from soot (Table 5) comprises no more than 3% of the soot mass, the balance being a fine, black amorphous material having physical properties consistent with elemental carbon.

Table 4: Concentration of primary organic compounds identified in vapor. (Courson, et al., 1996)

Compound	Air Concentration (μg/m3)
Phenol	1,600
Aniline	571
Diphenylether	190
2-methylphenol	125
4-methylphenol	106
Quinoline	42
Biphenyl	11
3-isocynatotoluene	10

Table 5: Concentration of major organic compounds extracted from soot. (Courson, et al., 1996)

Compound	Concentration in Soot (μg/g)
Quinoline	3480
Aniline	2990
1,2-dihydro-2,2,4-trimethylquinoline	2210
2-isocyanonaphthalene	2210
Phenol	2170
Fluoranthene	2130
Anthracene	1700
1-isocyanonaphthalene	1660
2-methoxyethoxybenzene	1660
Dibenzofuran	1360
n-hydroxymethylcarbazole	1290
2- and 3-methylaniline	1200
5-methylquinoline	1200
Diphenylether	1050

Analysis of combustion gasses revealed that levels changed significantly by varying the furnace ventilation rate, but not combustion temperature (Table 6).

Table 6: Different furnace ventilation rates significantly change combustion gas concentrations (mean ± s.e.m.; n=3)

Flow Rate (L/min)	**% CO** (max) (p=0.0910)	**% CO_2** (max) (p=0.0083)	**% O_2** (min) (p=0.0017)
340	0.373 ± 0.094	4.17 ± 0.487	15.68 ± 0.509
370	0.179 ± 0.015	2.60 ± 0.180*	17.83 ± 0.195
400	0.243 ± 0.101	2.54 ± 0.415*	18.14 ± 0.410
650	0.100 ± 0.007	1.72 ± 0.130	19.02 ± 0.088

*Statistically equal to each other

Particle Analysis

An initial characterization of the aerosol component showed that particle size and density were consistent with aerosols generated from other types of burning polymers. In addition to determining the chemical composition of the smoke, accurate assessments of particle size and smoke density are essential, as these parameters are used to calculate absorbed dose, probable zone of lung deposition, and expected mode of action. Several sampling methodologies are available which will measure both the physical characteristics of the particles and the amount of airborne material. Airborne concentration (mg/m^3) is used to calculate dose, which refers to the amount of material deposited in the respiratory system and is based on the amount of material in the air and the duration of exposure.

It is difficult to determine how much solid material was actually in the air, however, because of problems encountered with airborne sampling of the smoke. None of the particulate sampling devices used could endure the full ten minutes of a test burn without becoming clogged, so most samples were obtained only from the

leading edge of the plume as it traveled down the tunnel. Multi-stage impactors were fitted with a cyclone pre-filter to prevent the first stage from immediately becoming clogged with soot. Because these pre-filters removed particles greater than 10μm from the air stream, calculations showing a size distribution based on these air sampling data are not representative of the entire spectrum. Also, since the physical and chemical interactions taking place in the smoke plume are dependent upon both time and temperature, information obtained only from the wave front is of limited value. An accurate measurement of airborne particulate material along the length of the tunnel would have been extremely valuable.

Mass loss measured during combustion was approximately 30%; the material remaining in the furnace after combustion consisted primarily of the woven carbon fiber matrix. Air samples taken of the smoke plume during combustion did not reveal the presence of airborne fibrous material, a finding inconsistent with observations made at the site of an actual mishap (Olsen, 1993, Seibert, 1990, Formisano, 1989). Mass loss rate was highest at 770°C (6.0 g/min) and lowest at 880°C (2.4 g/min), according to calculations based on load cell readings during combustion. Changes in air flow did not significantly affect mass loss rate. Our nominal estimate of cloud density ranges from 6-10g/m^3, which means that substantial agglomeration and settling was taking place inside the tunnel, since these values are higher than physically possible. This is substantiated by observations that a large amount of solid material produced during combustion was clinging to the interior wall of the tunnel, due partly to electrostatic properties of the smoke, and partly to aerodynamic behavior of the particles. This phenomenon will affect interpretation of all collected data, regardless of sampling method.

Other techniques are available, though for calculating a particle distribution. Algorithms developed for analysis of scanning electron microscope (SEM) images were used to calculate the area, perimeter, and equivalent circle diameter of particles collected from the smoke plume (Table 7).

Table 7: Distribution of count median diameter (CMD), expressed as percent of total count (Courson, *et al.*, 1996)

Temperature Air Flow	< 1μm	1-5μm	5-10μm	> 10μm
625°C 340L/min	37.8	7.8	0.4	54.1
370L/min	30.1	8.6	1.5	59.6
400L/min	50.2	14.9	0.9	34.0
650L/min	44.2	5.5	0.4	49.4
770°C 340L/min	19.4	2.8	0.2	77.4
370L/min	30.9	10.3	0.3	58.5
400L/min	33.1	10.3	2.9	53.7
650L/min	26.4	4.4	0.2	68.9
880°C 340L/min	33.8	6.7	0.6	59.0
370L/min	38.6	8.2	1.6	51.6
400L/min	31.5	9.9	0.6	58.0
650L/min	53.5	6.2	0.8	39.5

A crude distribution may be derived from this table and when plotted on a log-normal scale, shows a bimodal character, from which some toxicological inferences can be made. Aerodynamic behavior of the particles, based on diameter, density, and shape, determines where particles will be deposited within the respiratory system. Particles greater than 10μm in diameter or less than 1μm are typically considered to be of less importance in pulmonary physiology since large particles tend to be filtered out of the airstream by the naso-pharyngeal system before entering the lungs and very small particles tend to be carried into and out of the lung without "sticking" to the internal surfaces. Particles smaller than 10μm, but larger than 1μm present the greatest hazard, since they tend to be carried into and deposited within the lung.

For this type of distribution, we would expect to see the larger fraction filtered out by the nose and mouth before reaching the lungs, while a portion of the smaller particles will likely be deposited deep in the lung. It is important to bear in mind that this distribution was obtained by computer analysis of SEM images. These images were made of material collected by gravitational settling of particles onto the floor of the exhaust tunnel. Very small particles will be less influenced by gravity than larger particles, so the calculated distribution does not measure smoke particles which were too small to settle out of the air stream.

Summary

The information required to accurately evaluate a pulmonary hazard from combustion products is very complex. Nuisance carbon dust deposited in the lung will present a physical irritation to the lung, activating a very effective mechanical and cellular clearance system. In a fire, however, it is not elemental carbon which is deposited, but an unequally distributed, complex assortment of liquid, gaseous, and solid material that will be deposited in different zones within the lung based on water solubility and particle size. This dynamic, complex environment is what makes accurate characterization so difficult. For example, some liquid phase material produced in a fire cools upon reaching ambient temperature and enters the lung as a solid. Solid material produced by the same fire and deposited on moist lung tissue may dissolve. Gasses evolved during combustion may have an anaesthetic effect on lung tissue, disabling the primary clearance mechanism. To further complicate things, chemical characteristics and particle size do not vary independently. Fortunately, technological advancements in the ability to measure and interpret data obtained from bench-scale combustion research are making the task more manageable.

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BURN HAZARD IN AIRCRAFT FIRES

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1. INTRODUCTION

Anyone who has seen a burn patient knows that burns are very traumatic, even life threatening, and often require more medical care than any other trauma. Moreover, the physical trauma is just the start; in many cases it is followed by psychological trauma. The psychological trauma can last a lifetime, daily reinforced by the disfigurement which often accompanies severe burns. Burn trauma teams now recognize this and employ psychological specialists who start therapy right along with the medical/physical therapy. All this extensive care costs a great deal of money.

For all concerned, the best course is to prevent fires through good design practice. For example, the US Army was able to cut the incidence of burn injuries in survivable crashes to nearly zero by equipping its helicopters with crashworthy fuel systems and having its aviators wear protective flight suits. Part of the justification for that retrofit program was based on the cost of treating burned aviators and training their replacements. The retrofit program turned out to be both the humanitarian and cost effective thing to do.

Part of calculating the cost/benefit of proposed fire safety measures is to be able to assess burn hazard with some accuracy. For example, one protective device worn by today's military pilots is their fire retardant flight ensemble. Historically these uniforms were tested in several ways. First, basic simple flammability tests showed which fabrics might be good candidates. The next step was to assess burn protective capability of various fabrics and fabric constructions. This protective capability was assessed by passing ensembles through fuel fires in an outdoor fire pit or by testing fabrics using pigs as aviator surrogates or by using heat flux sensors to measure heat transmitted through the ensemble and then using math models to predict the burn damage.

During the last AGARD-sponsored Aircraft Fire Safety Symposium, Knapp and Knox (1982) discussed the nature of aircraft fires and the testing of flight suit ensembles in some detail. Those who refer to that paper will find that the extensive bibliography was not published. The reader will find an expanded version of that bibliography in the BURNSIM User's Manual (Knox 1993) available from the authors.

The purpose of this paper is to focus on the burn prediction model, BURNSIM, and discuss its application to the study of fire/thermal sources in aviation. The model was originally developed to replace the use of pigs in testing protective fabrics, but subsequently has been applied to other cases such as side-by-side ejection seats, live fire testing and aerothermal heating during high MACH escape. Each of these applications will be discussed after presenting the burn model in some detail.

2. BACKGROUND

Aircraft fires vary widely depending on the fuel source, the aircraft type, and environmental factors. Light aircraft, such as utility helicopters, tend to heat up rapidly to as much as 2400°F (1315°C) in less than 20 seconds, while large cargo or passenger planes can resist burn-through for up to several minutes. Large fuel fires tend to have a high radiant component, while hot gas or hot surfaces can be convective or conductive. The spectrum of the thermal radiation will determine whether the energy is absorbed mostly at the surface or in depth. Once the energy is absorbed the heat is conducted within the skin or convectively removed by the blood. The net energy increase or decrease changes the temperature and when the temperature is above 44°C damage will result.

BURNSIM is a computer model which allows the user the convert heat flux incident to bare skin to a predicted burn depth. The requirement for such a model first arose when there was a need to quantify the thermal protective properties of new flight suits. Techniques employed in the 1960's and very early 1970's did not predict the full range of burns from no burn to full thickness and failed to take into account both initial conditions of the skin and its adaptive behavior when heated.

Beginning in the 1960's, the US Army Aeromedical Research Laboratory (USAARL) at Fort Rucker, Alabama, became involved in quantifying the burn hazard associated with post-crash fires and the protective capability of flight clothing. USAARL staff (including the author) conducted a number of field studies using burning helicopters to establish the severity and time course of post-crash fires (Knapp and Knox, 1982). They also 1) built and used two fire simulators to study the effect of simulated post-crash fires on pigs as human analogs (Knox et al., AGARD, 1978), 2) placed fabrics between the

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fire and the pigs to study their protective capability (Knox et al., ASMA, 1979), 3) assembled a large porcine (pig) burn database using this bioassay method (Knox, Final Report, 1979), and 4) developed the model, BRNSIM (now BURNSIM), to decrease the workload associated with using the bioassay method to assess fabric protective capabilities (Knox, 1979).

The starting point for building BURNSIM (short for Burn Simulation) was the work of Alice Stoll who based her model on Moritz and Henriques' damage integral (Moritz and Henriques, 1947). She had collected data from human volunteers on the time/heat flux relationships resulting in threshold transepidermal necrosis. This burn is represented by minor blister formation. To explain her results, she added a consideration of damage occurring during cooling as well as during the heating phase (Figure 1). Stoll chose the constants (Stoll and Greene, 1969) in her model to fit her human data on threshold burns; more severe burns were not at first considered. Later, Stoll (Weaver and Stoll, 1969) proposed an extension of her first model to include more severe burns without experimental basis.

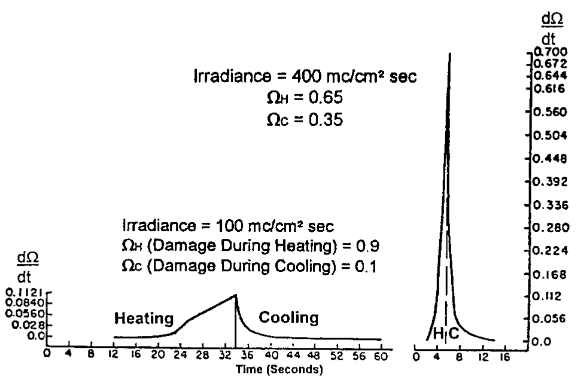

Figure 1. Damage Coefficient for Both Heating and Cooling at Two Different Irradiances

The first model to come out of the USAARL program was that of Art Takata of IITRI (Takata, 1974) who worked for USAARL as a contractor. He started with Stoll's approach and added water boiling as a way of handling blister formation. He then adjusted the constants activation energy (P) and frequency factor (ΔE) (see equation (7)) to predict USAARL's more severe porcine burns.

The current BURNSIM model expands on these earlier efforts (Henriques, 1947; Weaver and Stoll, 1969; Mehta and Wong, 1973; Morse et al., 1973; and Takata, 1974). It is an interactive model originally written in both FORTRAN and ZBASIC running on PDP 11/40, 11/03, 11/24, VAX 11/780, Macintosh and IBM compatible PC's. The latest version is written in C++ and Visual Basic to run on a PC in an MS Windows environment.

3. MODEL DESCRIPTION

BURNSIM considers the skin to be represented as 12 chunks or nodes (0,200....2200 um). Seven additional nodes can be inserted between the first and second nodes when exposures are mild and burn damage is likely to be shallow (Figure 2). BURNSIM solves the Fourier heat conduction equation to find temperature as a function of time at each node. Then total damage at each node is found by computing the damage integral at each depth. The transition between normal and damaged skin is defined as that depth where the damage integral is equal to one.

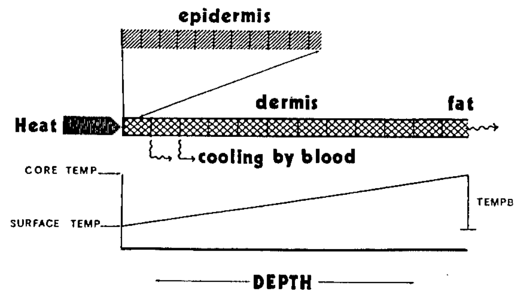

Figure 2. Skin Response to External Heating

3.1 Analytical Model

When Weaver and Stoll (1969) proposed extending Stoll's earlier model (Stoll and Greene, 1959) to heat fluxes higher than those used in obtaining her experimental data, they also found that the effective conductivity changed during the exposure and subsequent cool-down period. Takata (1974), using preliminary data from USAARL's Thermal Project, formulated a model which not only predicted threshold burns but deep burns and tissue water boiling as well. Starting with the work of Henriques (1947), Stoll and Greene (1959), Weaver and Stoll (1969), Mehta and Wong (1973) and Takata (1974), an analytical model was formulated as follows:

Human skin is essentially opaque to thermal radiation from exposures such as post-crash or in-flight fires, and can be considered to transfer energy internally by conduction only. Since exposure durations are no longer than the minimum response times reported for increased thermoregulatory system activity (1954) , thermal energy transfer in skin can be described by the Fourier heat conduction equation as follows:

$$r * Cp * \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K * \frac{\partial T}{\partial x} \right) + q \qquad (1)$$

where,

r = density, gm/cm^3
Cp = heat capacity, cal/gm-°C
K = thermal conductivity, cal/cm-sec-°C
T = temperature, °C

x = distance, cm
q = energy source, for the first nodal volume, cal/cm^3-sec

Since skin is considered to be opaque to radiant energy from a post-crash fire and since the source term is due only to radiant energy[1], equation (1) applies only to the surface of the skin. For all conditions in which x > 0, equation (1) reduces to the following:

$$r*Cp*\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K*\frac{\partial T}{\partial x}\right) \quad (2)$$

Solution of equations (1) and (2) requires two boundary conditions for x, preferably at x = 0 and x = L, and initial conditions at t = 0 for all positions 0 < x < L. If one assumes that there is no backward flux of thermal energy at x = 0 (all conduction is into the skin), then the energy flux at x = 0 is zero and, consequently, dT/dx = 0. Similarly, if the problem assumes that an adiabatic back wall condition prevails at x = L, the fatty tissue, then the net flux out of the system at x = L is 0, dT/dx=0. These two boundary conditions indicate that the system is closed and that all thermal energy added to the system, $0 \leq x \leq L$, is distributed within the system and cannot escape. Initial conditions specified a uniform temperature for all locations, $0 \leq x \leq L$, at time t = 0.

Consequently, the system may be defined by the following mathematical model:

$$r*Cp*\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K*\frac{\partial T}{\partial x}\right) + q \quad @\, x = 0 \quad (3a)$$

$$r*Cp*\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K*\frac{\partial T}{\partial x}\right) \quad @\, 0 \leq x \leq L \quad (3b)$$

T_L = CORE TEMPERATURE = TEMPI0 + TEMPB

$$T = T_O,\ 0 \leq x \leq L,\ \ t = 0 \quad \text{Initial Conditions} \quad (4)$$

$$\frac{\partial T}{\partial x} = 0,\ x = 0,\ 0 \leq t \leq x \quad \text{Boundary conditions 1} \quad (5)$$

[1] Simplifying assumption base on the predominance of the radiate mode of heating. May be less valid with fabrics. In actuality a correction is made to q to account for convective heating, surface absorptivity, and attenuation of radiant heating by hair

$$\frac{\partial T}{\partial x} = 0,\ x = L,\ 0 \leq t \leq x \quad \text{Boundary Conditions 2} \quad (6)$$

3.2 Solution of Mathematical Model

(Reneau and O'Young, 1976, 1977, 1978)

An analytical solution to equation set (3) was not considered feasible due to the variable nature of q, Cp and K, so explicit differencing methods of numerical analysis were employed to solve the equations. Reneau and O'Young (1976, 1977, 1978) employed the Crank-Nicholson six point implicit differencing (Crank and Nicholson, 1947) to the second-order partial derivatives and corresponding explicit methods to the first order partials.

This method is noted for the characteristics of stability and convergence when using correct increment sizes. The first model was implemented in FORTRAN IV using solution techniques of Thomas as described by Bruce et al. (1953). This initial model was revised to make it more realistic by allowing: energy flux across the surface, x = 0, during heating; convective heat loss at the skin surface during cooling; heat transfer into deep tissues including conduction into fat; convective cooling via the blood; tissue water boiling; a temperature gradient from surface to fat; and a gradient of thermal properties based on measured tissue water. The model, BURNSIM, is run interactively with the input and output variables listed in Table 1 changeable for each run.

From the relationship for first order kinetics assumed to apply in damaging tissue protein we have:

$$\text{Damage Rate} = \frac{d\Omega}{dt} = Pe^{-\Delta E/RT}$$

$$\text{Total Damage} = \int_{0}^{\text{ETIME}} d\Omega/dt + \int_{\text{ETIME}}^{\text{ITIME}} d\Omega/dt \quad (8)$$

If P = N x 10^y and $\Delta E/R$ = DE, then:

$$\ln\frac{d\Omega}{dt} = \ln N + y\ln 10 - E(T) = P_1 - DE*T_1 \quad (9)$$

where:

$$E(T) = \frac{\Delta E}{R}*\frac{1}{T}$$

$$P_1 = PL + PLN$$

$$T_1 = \frac{1}{T+273}$$

Table 1. Model Parameters Changeable Interactively

INPUTS:

TEMPI0 = Initial Surface Temp. (°C); 32.5 °C for man
DENS = Density of skin, 1.0 gm/cm^3
Q1 = Incident Heat Flux either constant or as a File of Fluxes, cal/cm^2-sec
BL = Skin thickness, 2200 um
AK = Calculation interval, nominally .01 sec. For short exposures, the calculation interval must be at least a hundred times less than the exposure duration.
JINC = Number of Nodes, nominally 12
TEMPB = Differences between TEMPI0 and backwall temp. (fat/core), °C. Note: TEMPI0 + TEMPB = Core Temp.
ABSORB = Absorptivity usually .613 assuming 10% convective and 90% radiative heating ; .94 for blackened skin
BOIL = Temperature when water boiling occurs, 100.15 °C
ETIME = Exposure Time, seconds
ITIME = Maximum calculation time usually 80-100 seconds
NXTRA = Number of extra nodes between the surface and node #2 at 200um, initially set at seven, used for superficial burns Note: The seventh node must be at 175um for an accurate time to pain prediction.
BLOOD = Factor to adjust amount of convective cooling by blood usually set at .001
DE1 & DE2 = ΔE/R from Arrehenius relationship for tissue temperatures from 44°C to 50°C, or over 50°C, respectively
DAMAGE RATE CONSTANTS = PL1, PLN1, PL2, PLN2, DE1, DE2 (for Nodes 2-12) APL1, APLN1, APL2, Constants APLN2, ADE1, ADE2 (for Nodes 1 and Extra Nodes)

OUTPUTS:

Flux (I) - tabulated heat flux as a function of time
DAMAGE, Ω - at each Depth (Node)
Maximum Temperature
Threshold Depth - in um (microns)
Time to Pain
Final Time - total calculation time
File of calculated temperatures - for later plotting by a standard graphics packages.
File summarizing simulation
File of temperature - as printed each second on the terminal

Thus, for damage calculations, the following constants are entered:

PL_1 (44°C - 50°C) = 1.46 PL_2 (50°C - 100°C) = 2.24

PLN_1 (44°C - 50°C) = 147.37 PLN_2 (50°C-100°C) =239.47

DE_1 (44°C-50°C) = 50,000 DE_2 (50°C-100°C) = 80,000

The program outputs dΩ/dt, for each node at each time step, total damage for each node and a threshold depth where Ω = 1. This depth is found using inverse interpolation on two or three w's nearest 1 using either y or log(y). Time to pain is also determined when the temperature at 175 um exceeds 44°C. Since the first presentations (Knox, Wachtel, and Knapp, 1978a, 1978c) BURNSIM has undergone further development.

3.3 Thermal Properties of Skin

Measurements of the water content of pig skin as a function of thickness were made on split thickness skin samples from several pigs. Given a table of measured values of water content as a function of skin thickness, a least-square cubic polynomial was fit to the data and water content as a function of depth was computed (Knox et al. 1986) from the following formula:

$$W(T-d) = \frac{T}{d}\left(W_T - W_{T-d}\right) + W_{T-d}$$

where T is the total thickness of the skin sample, W_T is the fraction of water computer from the cubic equation, d is the thickness of a thin slice at a depth T-d, and W_{T-d} is the fraction of water above the thin slice of skin.

Using the methods of Cooper and Trezek (1971), a profile of thermal properties was calculated for skin depths from 80 to 2000 um. A linear extrapolation of tissue water content from a depth of 80 um to the skin surface was made using a stratum corneum water content calculated from Rushmer et al. (1966) and the ambient percent humidity during the experimental phase of the project. This calculated water profile was used to complete the calculation of the thermal properties profile from 80 um to the skin surface. The thermal properties of the skin at 2200 um were assumed to be those of fat. These new thermal properties replaced those chosen by Morse et al. (1973) and used during previously reported simulations (Knox, Wachtel and Knapp, 1978a, 1978c).

3.4 Intraskin Temperatures in Pigs

In earlier simulations (Knox et al., 1978a, 1978c) it became apparent that unless the temperature calculations reasonably represented what actually occurred in the skin, adjustment of the values for PL, PLN and DE in the damage equation to match a few burn depths would not be likely to result in a model which works well for all cases. Fortunately, 11 intraskin temperature profiles were recorded on FM magnetic tape during the experimental phase of the program. These voltage records were digitized and converted to tables of temperatures at 100 samples per second.

Figure 3 presents the one-page summary report from a simulation of the exposure of Pig 294RF to a 3.47 cal/cm^2-sec JP-4 fuel fire for 3.02 seconds. Note that boiling occurred (confirmed by blister formation, Figure 4) and that the surface reached a maximum of 128.7°C. Predicted threshold depth was 1528 um and observed depth was 1465 um. One observed temperature profile is overlaid on the calculated temperature

profiles (for nodal depths of 0, 200, 400....2200 um) in Figure 5a. The oscillations in the observed temperature profile are most probably due to a "hunting" in the autoregulation of tissue perfusion by blood. The frequency, for example, is similar to that seen in studies of microcirculation.

3.5 Validation of BURNSIM for Human Beings

Stoll collected data from human volunteers who exposed their arms and hands to a well controlled radiant source (Stoll and Greene, 1959). They collected time to pain and surface skin temperature, and noted the severity of burn. In one exposure of blackened skin to 400 mcal/cm^2/sec for 5.6 sec, she noted minor blister formation within 24 hours.

When BURNSIM, which accurately predicted a deep dermal burn in pigs above, is changed to simulate this case (ETIME = 5.6 sec, Q = 0.4 cal/cm^2/sec, absorb. = 0.94) the result is a predicted burn of 104.6 um (near the transition between epidermis and dermis). The time temperature plot (Figure 5b) shows that the predicted surface temperature follows Stoll's measured surface temperature quite faithfully.

```
MODEL NAME OR DESCRIPTION: PIG 294RF ABS 0.613

                        SKIN DIFFUSION DATA
                        INPUT PARAMETER LIST

TEMPIO=   34.9700       DENS=    1.00000         Q1=   3.47000
BL=   .220000           AK=    .100000E-01       JINC=    12
TEMPB=  3.3600          ABSORB=    .613000       BOIL=   100.150

APL1=   .780000         APLN1=   285.520         ADE1=   93534.9
APL2=   .600000         APLN2=   117.430         ADE2=   39109.8

PL1=       1.46         PLN1=    147.37          DE1=  50000.00
PL2=       2.24         PLN2=    239.47          DE2=  80000.00
ETIME=       3.02       ITIME=     80.00         NXTRA=   8
BLOOD=      .0010

EXTRA NODES:   22.2  44.4  66.7  88.9 111.1 133.3 155.6 177.8

FLUX FILE I.D.:                .00   2

 FLUX(I)=
   1   3.470    2   3.470

V=          .39950E+01
V=          .40733E+00
V=          .45290E-01

D=          .72442E+01
D=          .73778E+01
D=          .74955E+01

V =          .19755E+19     AT DEPTH (IN MICRONS)=          .112535E-06
V =          .82482E+12     AT DEPTH (IN MICRONS)=          200.000
V =          .26532E+09     AT DEPTH (IN MICRONS)=          400.000
V =          .57713E+06     AT DEPTH (IN MICRONS)=          600.000
V =          .84775E+04     AT DEPTH (IN MICRONS)=          800.000
V =          .44473E+03     AT DEPTH (IN MICRONS)=          1000.00
V =          .39319E+02     AT DEPTH (IN MICRONS)=          1200.00
V =          .39950E+01     AT DEPTH (IN MICRONS)=          1400.00
V =          .40733E+00     AT DEPTH (IN MICRONS)=          1600.00
V =          .45290E-01     AT DEPTH (IN MICRONS)=          1800.00
V =          .89902E-02     AT DEPTH (IN MICRONS)=          2000.00
V =          .00000E+00     AT DEPTH (IN MICRONS)=          2200.00

MAXIMUM TEMPERATURE =  128.724

THRESHOLD DEPTH =               1528.

FINAL TIME =   80.00
```

Figure 3. BURNSIM Summary Report For Pig Test 294

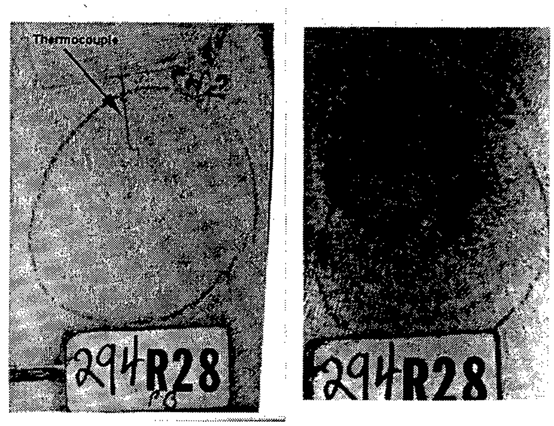

Figure 4. Burn Site Prior to Exposure (Left) Showing Intraskin Thermocouple and After Exposure Showing Blister Formation

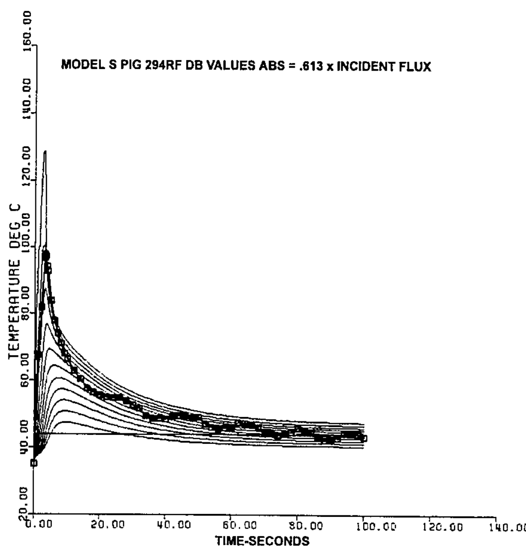

Figure 5a. Predicted Skin Temperature at Each Node (Solid Lines) and Measured Intraskin Temperature (Squares)

3.6 Validation From a Large Study of Pigs Exposed to a Carbon Arc Lamp

Lyon et al. (1955) exposed pigs to various combinations of heat flux and exposure time to map the relationship between applied thermal energy and burn severity. BURNSIM was used to simulate their data and an example of the results are shown in Figure 6. The plot overlays the model prediction on the observed cumulative distribution of observed burn severity. For these cases the heat source was a carbon arc lamp which has much of its energy in the visible spectrum.

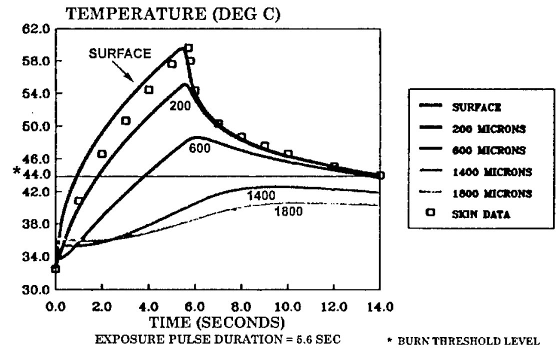

Figure 5b. Comparison of BURNSIM Generated Skin Temperature to Measured Skin Temperature Date

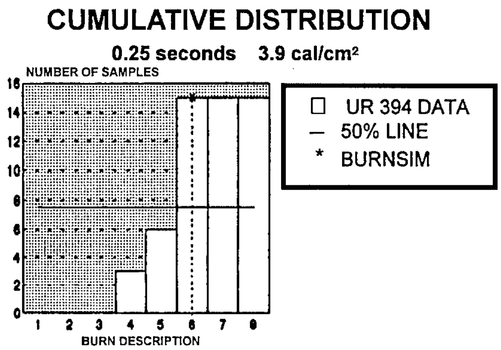

Figure 6. Observed Cumulative Distribution of Burn Severity with Estimated BURNSIM Prediction

Davis (1959) showed that this energy is absorbed in depth rather than just at the surface. It is not surprising that the model's predictions are on the high side, especially taking into account that the observed burns Takata used in selecting the activation energy and frequency factor for dermal burns were graded as the worst area of burn damage within the burn site.

4. USES OF BURNSIM

4.1 Side-by-side Ejection Seats

As Figure 7 shows, the T-46 had side-by-side ejection seat. During testing, it was noticed that the flight suit of the second manikin to eject was damaged by the rocket of the first seat. BURNSIM was used to assess the effect of the rocket exhaust. Heat flux measurements were used as input to BURNSIM. The results showed a chance of burn damage could be averted if the ignition of the first rocket were delayed a small amount.

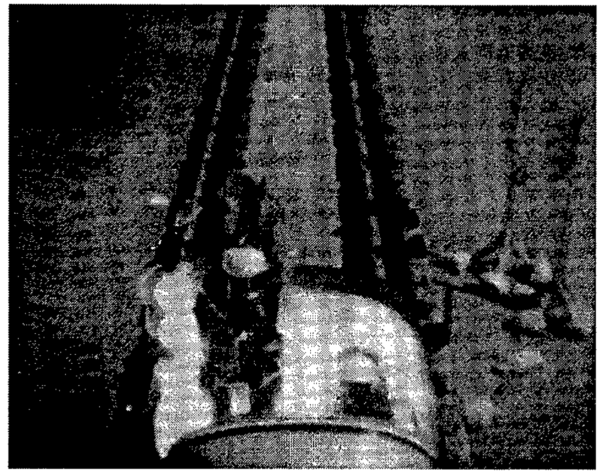

Figure 7. Manikin Ejection from a T-46 Forebody During Sled Test at Holloman AFB

4.2 High Mach Escape

Computational fluid dynamics was used to simulate the aerothermal heating expected to occur as a pilot ejects at supersonic speeds. Figure 8 shows the predicted heat distribution in one such simulation. BURNSIM was used by McDonnell Douglas to find the speeds and altitudes where burn injury was a problem. During an ejection of the Russian K-36D seat at 50k+ feet and Mach 2.5, some heating of the flight ensemble was noted. BURNSIM showed that there was no danger of burns at these conditions.

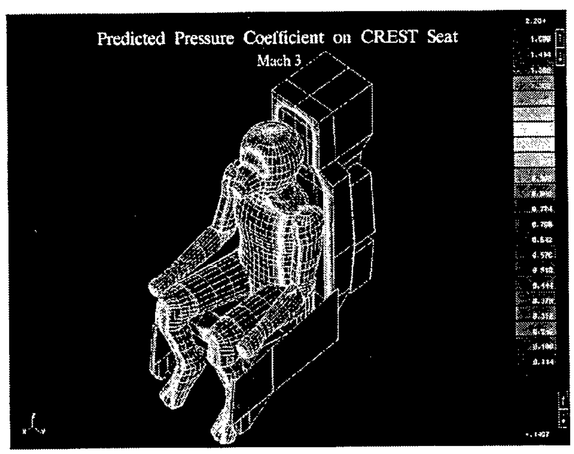

Figure 8. Predicted Heat Distribution Due to Aerothermal Heating During Supersonic Ejection

4.3 Fabric Insulating Capability

Seven fabrics were subjected to a 2.2 cal/cm^2*sec radiant (quartz lamp) source for about six seconds. The plots in Figure 9 show the difference between the fabrics. Two were obviously

good insulators. In a similar study, four fabrics and several pigs were subjected to a JP-4 fuel fire. Heat transfer was measured by calorimeter and by actual burns on the pigs. Figure 10 shows that the burn depths predicted by BURNSIM match the observed burns in the pigs using the four different fabrics.

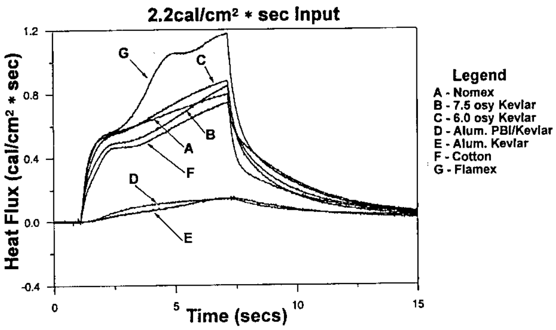

Figure 9. Transmitted Flux for Various Fabric Samples Exposed to a 2.2 cal/cm^2 *sec Flux Input

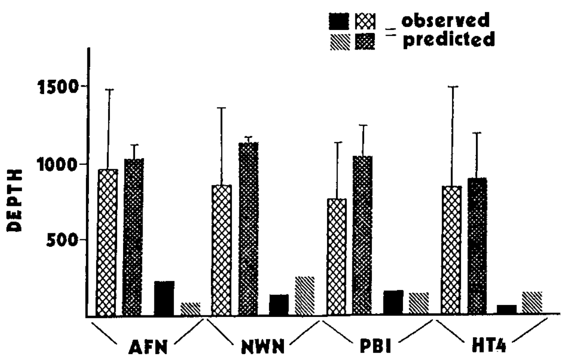

Figure 10. Predicted Burn Depths Under Four Different Fabrics at Two Different Heat Flux Inputs

4.4 Burn Hazard During Live Fire

An F-15 fuselage was instrumented with heat flux sensors (Figure 11a) and then shot with various types of ammunition. The fluctuating heat flux recorded at the right hand of the manikin (Figure 11b) was sufficient to cause a deep dermal (1413 um) burn at the right hand. This case illustrates that BURNSIM handles any shape time varying flux as an input. Thus, it is ideal for analyzing data from aircraft fire tests where the flux fluctuates. It also points out that the next addition to the model needs to account for the clothing worn by the crew exposed to the fire. Both an analytical and a filter approach have been explored. A simple first-order filter can be used quite successfully to simulate the insulating properties of a single layer. Filters can also be cascaded for more complex ensembles.

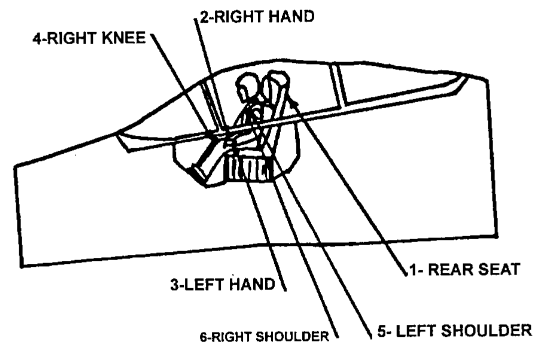

Figure 11a. Heat Flux Sensor Placement for Live Fire Test

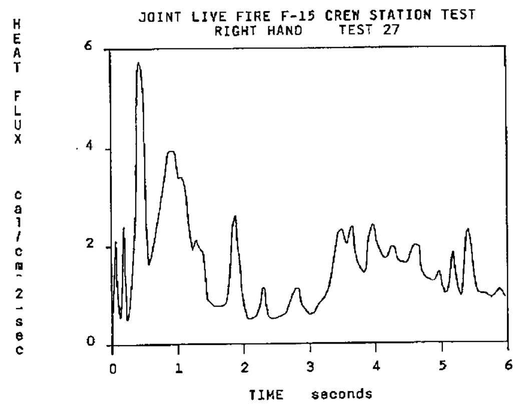

Figure 11b. Heat Flux Measured at Right Hand of Manikin During Live Fire Test

4.5 Other Models In Use

Since the publication of BURNSIM, various other authors have used finite element models to study the effect of burns. Diller and Hayes (1983), and Torvi (1992), for example, have written finite element models and studied their performance in predicting burn injury resulting from hot surface contact (Diller and Hayes) and flash fires (Torvi). Behnke, Geshury, and Barker (1992) and Dale et al. (1992) have employed models with instrumented mannequins to assess the protective capability of fabrics. More recently, Lawton and Laird (1993), employed such a model to investigate skin burns behind defeated armor. They showed that, for high temperature thermal sources, in-depth absorption of heat flux improves the accuracy of burn predictions. The general success of BURNSIM and all the other models supports their use in assessing the burn hazard associated with aircraft fires. Experimentally, it is only necessary to measure heat flux as a function of time during the fire and then use BURNSIM or similar model to process the data. Predictions of time-to-pain, maximum temperature and burn depth are possible. If an instrumented mannequin

is used, then burn area can be assessed as well. To our knowledge BURNSIM is the only such model set up to be interactive to facilitate conducting what-if studies as well as data reduction.

5. CONCLUSIONS

BURNSIM is available for those wishing to conduct analyses of data collected during experiments with protective clothing, aircraft fires, high-speed ejection seats and other cases when what-if studies are called for.

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DISCUSSION - PAPER NO. 32

H. Weyer (Question)

What is the relationship - in an open fuel fire - between heat transfer and radiation?

Dr. Knox - Author/Speaker (Response)

The total heat flux from an open fuel fire is predominantly (70-90%) radiation and the rest convection. This large radiative component makes the optical properties of the absorbing surface, be it skin or clothing, important. Depending on the temperature and the emissivity, the radiation will have a specific spectral distribution. At visible and very short IR wavelengths some the radiation is absorbed in depth in the skin. At longer IR wavelengths, most or all is absorbed at the surface. The model uses a total heat flux as input. This total is the sum of all thermal energy incident at the surface. It includes: radiation, convection and conduction (if some hot or cold surface is touching the skin). The absorbtivity parameter is used to adjust for the portion of the radiation not absorbed, while the convective portion is assumed to be totally absorbed. Experimentally what one does is to measure the radiation with a radiometer and the total flux with a calorimeter. From the two, you can calculate what fraction is convective.

Unknown **(Question)**

Has there been any research performed on the effect of burns to the eye, and is the eyelid skin of the same composition as say the skin on the arm?

Dr. Knox - Author/Speaker (Response)

Regarding burns to the eye, the simple answer is that there has been research performed. Let me suggest two sources:

- A.J. Welch and G.D. Polhamus, Measurement and Prediction of Thermal Injury in the Retina of the Rhesus Monkey, IEEE Transactions on Biomedical Engineering, Vol. BME-31, No. 10 Oct. 1984. There are 46 references.
- Thomas Wachtel, MD, Past President of the American Burn Association, Sharp Memorial Hospital, Trauma Service, 7961 Frost St. San Diego, CA 92123-2788. Tom is a colleague who has been a Burn Surgeon since the late 1960's.

According to Bloom and Fawcett Text of Histology, the skin of the eyelid has the same general structure but is thin (0.6mm or less) and has layers of fat and muscle below. Skin of the arm is 1 to 2 mm thick.

On the Composition of Combustion Gases Occuring after Flight Accidents and Incidents and their Analytical Proof of Existence

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1 Abstract

In the course of flight accidents and incidents, diverse fires are frequently occurring. As a result, there are mostly gaseous or highly volatile combustion and pyrolysis products are arising which depend on the fire conditions (ventilation, temperature etc.), the POL (petrol - which is jet fuel, aviation gas, oil, lubricant) in use and the plastic and compound material used in the manufacture of modern aircraft with their characteristic compositions.

The exact knowledge of such products and their toxicological qualities is of major importance as well as their definite proof of existence when, according to forensic standards, such occurrences are investigated for possible impairment of human health as a result of flight incidents.

The present study provides an overall view of gaseous or highly volatile products possibly resulting from post-crash and in-flight aircraft fires, together with the first results from a new, high-resolution analytical system for definite substance identification which were obtained at the German Air Force Institute of Aviation Medicine.

2 Introduction

Flight accidents and incidents are generally unexpected and sudden occurrences frequently claiming the lives of the aircrew, the passengers and sometimes innocent third persons involving, moreover, considerable material and other losses. Therefore, the cause of the flight accident must be very carefully clarified, because it might have far-reaching *legal consequences* as e.g. punishment, damage claims, and possibly the loss of a person's career.

In this context, determining the exact cause and time of death is of decisive importance. Pertinent literature states enough examples when, in flight, the pilot suffered from a myocardial infarction or a stroke, or a coronary or circulatory debility which only became evident under flight stress, or from other serious physical disturbances [1]. In such cases, the pilot's death was not the consequence but the cause of the flight accident.

It is known however that, apart from these rather organic causes, toxicological influences due to unauthorized medication, illegal drug or alcohol consumption, POL- (which is jet fuel and aviation gas, oil and lubricants) or engine gases polluting the air conditioner or gases of a fire broken out or smouldering on the aircraft may cause serious impairment with a consequent flight accident or incident [1, 2].

After a flight incident, the flight surgeon in charge may frequently ask the question if POL, engine or combustion gases have been taken up in relevant quantities as to give reason to expect acute or chronical impairment to the health of the aircrew. Looking carefully into the respective history and moreover, toxicological examinations of blood and urine samples will help to assess the respective case.

As a matter of routine, Division V - Forensic Medicine and Medical Investigation of Aircraft Accidents - of the German Air Force Institute of Aviation Medicine investigates all the flight accidents and incidents involving any German military aircraft, and also civilian aircraft crashing mostly in the south German air space. Our Division closely cooperates with the competent authorities in charge of the inquiries and the Flight Accident Investigation Center (Flugunfalluntersuchungsstelle, FUS) of the Federal Office of Civil Aeronautics (Luftfahrtbundesamt, LBA), the local flight surgeons, as well as other competent Air Force units in order to settle the above-mentioned questions completely. So, in the last three years we performed forensic investigation of 155 flight accidents or incidents and worked out the respective reports for the Prosecution or the law courts as well as for the German Air Force.

3 Inflammable Materials Aboard an Aircraft and the Resulting Combustion Gases

In aircraft accidents and incidents, a great number of different materials are inflammable and thus susceptible of creating toxicologically relevant products.

Jet fuel and aviation gas is available in vast quantities and highly inflammable and thus may give origin to enormous quantities of combustion gases. Such products are normally manufactured by distillation of crude oil and depending on the fraction used they have typical boiling ranges (e.g. kerosine 150 and 300 Centigrades). Like the jet fuel F34 which is almost exclusively used by the German Air Force jet airplanes and by the NATO-partners, they contain in the first place [3]

- saturated hydrocarbons (alkanes and cycloalkanes),
- unsaturated hydrocarbons (alkenes, 5% max.)
- aromatics (like e.g. benzene, toluene, and naphthalene, 22% max.)
- impurities generated by technological pollution, such as
  - sulphur (e.g. sulphides, disulphides and thiopene 0.3% max.)
  - sulphurous hydrocarbons (e.g. mercaptane, 0.002% max) and
  - nitrogenous compounds (pyridine, and homologous substances).

Different additives are mixed into jet fuel and aviation gas to improve their qualities:

- anti-oxydants (e.g. 2, 4, 6-trimethyl-phenol, phenylenediamine),

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

- fuels system icing inhibitors (FSII, e.g. ethylene glykol monomethylether, EGME),
- metal deactivators (MDA, e.g. N,N'-disalicylidene-1,2-propane-diamine),
- corrosion inhibitors/lubricity additive (e.g. high molecular carbonic, sulphonic and phosphoric acids as well as their anorganic and organic salts),
- static dissipators (SDA)

The other POL (e.g. oils and lubricants) contain specific fractions of mineral oil or synthetic oil respectively, and are mixed with different additives in a very similar way. The different cleaning, deicing and other agents do not have any uniform composition but very often they contain organic solvents e.g. alcohols. The named additives, however, are toxicologically of minor importance. They may be meaningful in situations, were one must *identify* the POL. Practically speaking, hydrocarbon percentages alone are relevant and particularly the products eventually arising from pyrolysis and oxidation in a fire. There are several publications whose subject is precisely the investigation of such substances [16, 15, 12, 23, 20, 13, 9, 30].

On the first place, there is doubtlessly carbon monoxide (CO) arising specially under oxygen shortage and high fire temperatures and which is of particular toxicological importance due to its excellent bond characteristics to haemoglobin. Under reduced oxygen supply, however, a lot of other products may arise from pyrolysis or incomplete oxidation of the stated hydrocarbons like e.g. alcohols, phenols, esters, organic acids, ketones, aldehydes and others. Carbon dioxide (CO_2) arising under sufficient oxygen supply is of minor toxicological importance and, if ever, may have a decisive function for displacing oxygen.

Carbon monoxide, unalterated POL and the various oxidation products must be rated as important markers proving the suspected absorption of combustion gases during a flight incident.

In modern aircraft manufacture, **plastic and other compound material** is frequently used. Many different and highly toxicological products may develop in a fire or under any other thermal stress (as for example in a short-circuit) [33, 31].

Insulation of electrical wires in aircraft often consists of materials containing high percentages of polyvinyl chloride (PVC). In a fire or during any other thermal stress, cancerogenic substances may be created such as vinyl chloride and benzene as well as phosgene, hydrochloric acid (HCl) and, under unfavorable conditions, even various dioxines. In the latest aircraft manufacturing techniques, polytetrafluoroethylene (PTFE) is used for insulation of electrical wires. This material resists to higher temperatures, however, when a fire breaks out it tends to disintegrate into toxicologically highly relevant fluoric compounds, like hydrogen fluoride (HF, hydrofluoric acid).

For seat construction and for heat and noise insulation polyurethane foams are often applied. It is a known fact that under low combustion temperatures such materials produce hydrogen cyanide (HCN, prussic acid) [33, 31]. By the way, this extremely toxic gas is also generated when materials like polyacrylnitril or nylon are burning. When combustion temperatures are rising, other toxicologically relevant products are set free just like acroleine, ammonia and nitric oxides.

Due to their good combustibility together with the strong development of soot and smoke, today fire and smoke inhibiting agents are mixed in most plastic materials. Although the aromatic bromine containing substances meet with the intention, they create other bromine substituted dioxines and other compounds giving rise to new toxicological problems.

Apart from the above-mentioned materials corresponding to the aircraft manufacturer's design, combustion and pyrolysis products must be taken into account possibly arising from a cargo. But on such materials detailed information will be required; otherwise it is out of the question to make any prior assessment on any products possibly arising under combustion.

The substances which are *effectively* produced during an aircraft fire depend to a large extend on the conditions (combustion temperature, oxygen supply, presence of other flammable materials, etc.) and simply cannot be predicted. By experience, each flight accident and thus each post-crash fire is unique [4]. For standardization purposes, however, now and then more precise models are being worked at to be able to pre-assess the products emanating from an aircraft or other fire and their toxicological consequences [12, 30]. In addition to the products already stated above, there are obviously soot, dust, nitric oxides (NO_x) and, possibly, sulphur oxides (SO_x).

Part of the toxicological characteristics and biological effects of the individual components of combustion gases have been very well investigated in the past; this applies particularly to the main substances like CO, CO_2 and HCN. However, very little is known about the *global effect* of the combustion gases whose composition becomes ever more complex [30, 32, 31]; therefore, further research work is urgently required in this field. Considering the great number of substances alone, this is an extremely difficult task. The total number of gases so far identified when six important types of plastic pyrolize or burn is listed up in the following table 1. It must be mentioned, that this numbers increase every month.

Plastic	Number of identified substances
Rigid polyurethane foam (PU)	121
Polyester (PE)	69
Acrylonitrile-butadiene-styrene	27
Polyethylene	167
Polystyrene (PS)	59
Polyvinyl chloride (PVC)	81
Nylon	110

Table 1: Number of substances identified when six important types of plastics pyrolized or burned [33].

4 Methods

According to the above considerations, when POL or combustion gas exposure is suspected, any routine investigation must first be confined to the principle markers such as carbon monoxide CO und the respective POL as well as to all the other volatile substances. If significant COHb-values, exceeding say 10% are detected, cyanide or hydrogene cyanide should be searched. It will depend upon the results if any further examinations are required.

Carbon monoxide combines extremely well with hemoglobin thus reducing the amount of hemoglobin available for oxygen transportation in the blood. For determination of the resulting *carboxyhemoglobin* (COHb), various

- photometric and
- gas chromatographic

methods are normally applied [2, 22, 16, 15, 4]. Apart from financial aspects the choice of the method depends on the respective material and problem to be investigated.

Photometric methods measure absorbance at not only one but at various essential wavelengths to differentiate the COHb at stake from the other hemoglobin species (e.g. deoxyhemoglobin, oxyhemoglobin, methemoglobin and sulph-hemoglobin). Nevertheless these methods are ineffective with low carboxyhemoglobin concentrations.

When bodies are very much disintegrated, it is not possible to take suitable blood samples and thus carboxyhemoglobin cannot reasonably be determined by photometric methods. In such cases *gas chromatography* is the method to be chosen and, if necessary, even carbon monoxide bound to myoglobin has to be determined. In the first place columns packed with molecular sieves are still used, in some cases however even capillary columns are chosen. In general, heat conductivity detectors bring the results. One author reports the usage of a reduction detector [15]. The great advantage of gas chromatographic methods is their higher specificity and their capacity to indicate values below 3% of COHb (carboxyhemoglobin), when photometric procedures would only produce unsatisfactory results.

Division V - Forensic Medicine and Medical Investigation of Aircraft Accidents of the German Air Force Institute of Aviation Medicine uses - on a routine basis - a photometric method measuring nine important wavelengths. The values of 1-6% thus obtained after flight accidents and incidents without any casualties nicely correspond to the values reported for non-exposed smokers and non-smokers in the respective literature [1, 22, 2, 4, 16, 12].

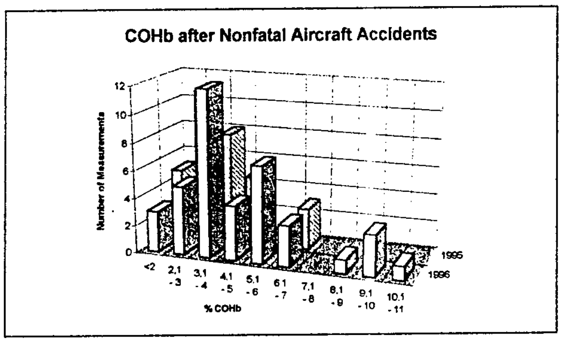

Figure 1: COHb-values obtained after flight incidents (1995 and 1996)

When, after a flight incident in 1996, 9 to 10% COHb were detected in five blood samples, this was not surprising when the circumstances of the accident were known: the patients evidently had smoked several cigarettes one shortly after another, immediately before the blood samples had been taken. The existence of any POL (aviation fuel or the like) or any other significant volatile substances could not be proved in this case. In the years 1995 and 1996, COHb-contents not exceeding 10% were ascertained after flight accidents with death casualties.

Tests for **Cyanide** were essentially performed in the following way:

- photometric determination of colored complexes, developing from chloramine-T and pyridine/barbituric acid with hydrogen cyanide set free after acidification [22] or by microdiffusion [2], or by
- gas chromatographic separation on packed or capillary columns [18] and determination of hydrogen cyanide set free after acidification and registration at the NP-detector.

Both methods provide high sensitivities and are sufficiently specific. In Division V – Forensic Medicine and Medical Investigation of Aircraft Accidents at the German Air Force Institute of Aviation Medicine we are in a position to perform examinations according to both methods.

According to the preceding considerations, **POL** and the resulting **pyrolysis and combustion products** consist of a large number of various individual substances. As packed columns do not sufficiently separate substances from one another, they are considered to be unsuited for proving exposure analytically. In view of most recent findings only gas chromatographic procedures including capillary columns with high resolution capacities are feasible; moreover, flame ionization detectors (FID) will be applied to register chromatograms according to each problem under investigation [2, 5, 23, 24]. Although these strong detectors have sufficient sensitivity for proving the existence of substances containing carbon and hydrogen, they do not allow for identifying the individual components. This lacking quality can at least partly be compensated by double column technique or multidimensional gas chromatography, often combined with various element specific detectors.

Thanks to their excellent identification qualities combined with high sensitivity, mass spectrometric methods have successfully been introduced in this field, too [19, 8, 9, 13, 14, 20, 34, 28, 27, 26, 21]. Many POL substances and their combustion gases are very similar and therefore they show similar characteristics in terms of mass spectrometry. Nevertheless, when related to the retention times, a definite identification of the individual substances is possible in most cases.

As concentrations of substances to be traced are usually very weak it is necessary to intensify them and to remove interfering matrix components. For this purpose, diverse

- Headspace techniques (HS);
- Purge & Trap Systems (P&T) and
- (Headspace) solid-phase micro extractions (SPME)

are applied.

In the *Headspace method* [29, 28] an assay is slightly warmed in a closed vial and then an aliquot of the steam space is examined in the gas chromatograph. In the *Purge & Trap technique* all the volatile substances of an assay are purged out by way of a carrier gas stream and trapped upon an adsorptive medium. After a definite time, this adsorptive medium is quickly heated up and the mixture of substances again desorbed is injected into the gas chromatographic system. The *Headspace solid-phase micro extraction* (SPME, [6, 25]) may be considered a variety of both methods combined. Like in the Headspace procedure the assay is first heated up in a closed vial. Thereafter, a thin solid-phase fibre is installed in the headspace by means of a special device. After a certain adsorption time, this solid-phase fiber is taken to the injector of the gas chromatograph, where the adsorbed substances are again desorbed.

In the gas chromatographic system the complex mixture of substances is finally split into individual components, their qualities and - possibly - quantities are detected and identified by mass spectrometry (GC/MS).

In the past, Division V - Forensic Medicine and Medical Investigation of Aircraft Accidents of the German Air Force Institute of Aviation Medicine has elucidated such questions by manual or automatic Headspace sample introduction, separation by means of packed or capillary columns and flame ionization detection. Since May 1996, however, we have had at our disposal a much better fitted analytical system, consisting of

- one Purge & Trap System (HP 7695), equipped with a trap HP Vocarb 3000, and
- a gas-chromatographic and mass-spectrometric system for separation and identification (GCD G1800A), with a capillary column HP-VOC, length: 90m, inside diameter: 0.32 mm. The layer thickness of the stationary phase is 1.8 μm and helium is taken as carrier gas with a 1.8 ml/min flow rate.

5 Results

Since the system has been introduced and set in operation, about 160 measurements were performed so far with

- standard aqueous solutions with individual substances or mixtures whose exact composition and concentration we knew (calibration),
- blood and urine samples without exposure (which were taken and immediately analyzed and parts of them were left to themselves untreated and analyzed later)
- highly diluted aqueous solutions of various gasolines, diesel oils, jet fuels, and aviation gases
- blood and urine samples mixed with petrol or jet fuel substances,
- various blood and urine samples taken at flight accidents or incidents, and
- tissue samples taken after a suspected violent crime.

The chromatogram of the measured aqueous standard solution shows that when taken under this optimal conditions each of the substances benzene, toluene, and the isomeric xylenes, which are frequently used as markers for fuel or combustion gases exposure, can presumably be identified and quantified in concentrations much below 10 μg/l (compare Fig. 2). Not only based upon our own measurements it is doubtful whether these substances are suitable as markers, at least in the range of weaker concentrations [17].

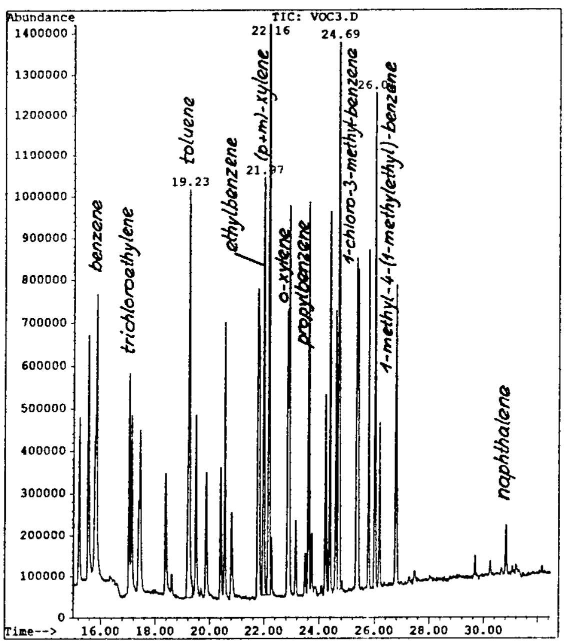

Figure 2. Total ion chromatogram (TIC) of an aqueous standard mixture of various volatile substances (VOC) in a 10 μg/l concentration/each.

It is evident that the resulting sensitivity at the presence of a matrix is not as favorable. When 10 μg/l jet fuel F34 have been added to a urine specimen (comp. fig. 4), measurements show that essential components can easily be identified and quantified in this matrix, like toluene, o-, m- and p-xylene, propyl benzene etc. Naturally, the classical comparison with typical peaks can also be performed independently of the identification of characteristic individual components.

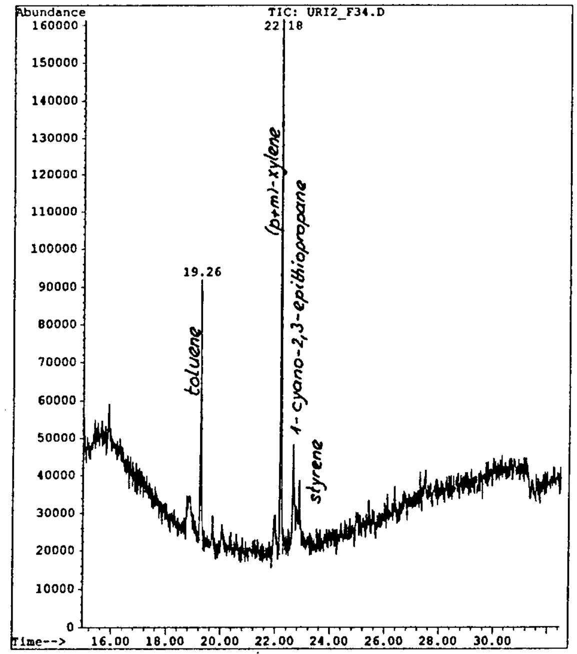

Figure 3: Total ion chromatogram (TIC) of a non-exposed urine specimen

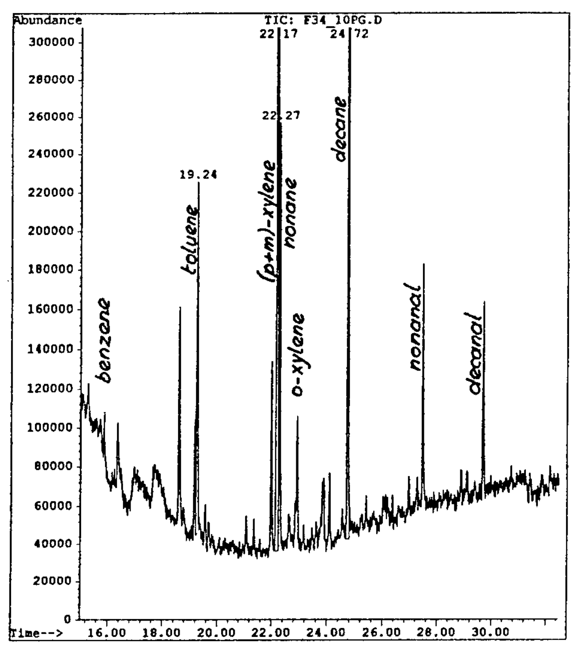

Figure 4: Total ion chromatogram (TIC) of a urine specimen with 10 μg/l F34 jet fuel added

Applying the above-mentioned system we examined blood samples which were artifially contaminated by the exhaust gases (jet fuel F34) of jet aircraft: by mass spectrometry more than 100 new peaks could be registered which did not exist in the non-contaminated blood samples (comp. fig. 5). Among others the following substances were detected: chloroforme, benzene, formicacid-heptylester, toluene, 1-octene, 3,5,5-trimethyl-hexane, ethylbenzene, isomeric xylenes, nonane, phenylethyn, styrene, 1-methyl-ethyl-benzene, propyl-benzene, 4,4-dimethyl-heptane, tribromo-methane, 2-pentyl-furane,

various trimethyl- or ethyl-methyl-benzenes,respectively, benzofurane, 1-methyl-4-(methylethyl)-benzene, (1-methylpropyl)-cyclohexane, various diethylbenzenes, indene, various methyl-propyl-benzenes, 2-ethyl-1,4-dimethylbenzene, 1-methyl-2-(1-methylethyl)-benzene, 1-ethyl-2,4-dimethylbenzene, 4-tert-butyltoluene, 1-methyl-4-(2-propenyl)-benzene, various tetramethyl-benzenes, (1-methyl-1-propenyl)-benzenes, naphtaline, 1,2,3,4-tetrahydro-methyl-naphthaline.

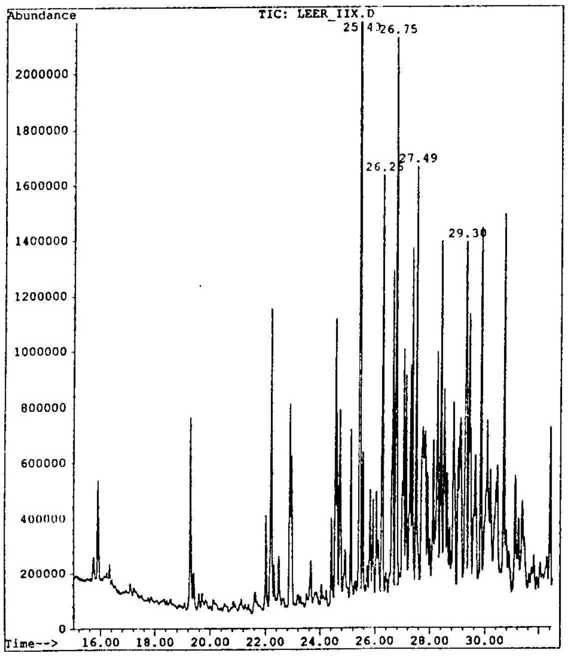

Figure 5: Total ion chromatogram (TIC) of a blood sample artificially contaminated with exhaust gases (F34) of a jet engine (no-load running)

Substance	Retention time (min)	Concentration (pg/μl)
Chloroforme	14,37	8,3
benzene	15,90	11,0
toluene	19,28	12,5
p- und m-xylene	22,20	10,0
o-xylene	22,94	9,2
propyl benzene	24,40	6,2
naphthalene	30,70	49,0

Table 2: Several important compound concentrations detected in a blood sample polluted by jet engine exhaust (no-load running) (compare Fig. 5)

Assessing the sensitivities as reported (comp. table 2) it must be taken into account that complete mass spectra in a 33 to 270 m/z range were registered. If only a few ions were to be registered exclusively (SIM-Mode), a further increase of sensibility would certainly be achieved at the cost of a reduced identification safety.

Some of the substances identified with the help of the common MS-Libraries (e.g. Wiley, NIST) are certainly very controversial due to the mass spectrometric similarities which are known to exist within homologous series for example. So, the identifications, for lack of authentic substances suitable for comparison cannot always be verified.

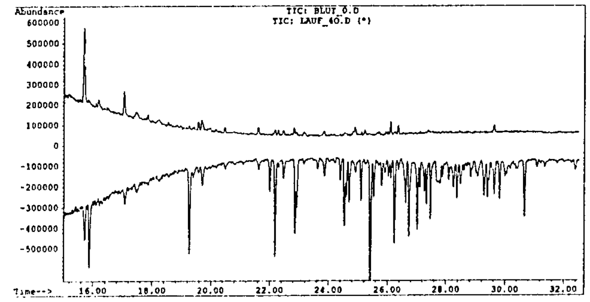

Figure 6: Chromatogram of total amount of ions of a blood assay before (upper chromatogram) and after contamination by jet engine exhaust (jet fuel F34, 70% full load, lower chromatogram)

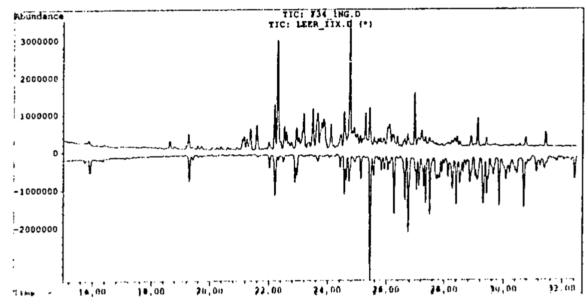

Figure 7: Comparison between the chromatogram of the total amount of ions of a blood assay which was polluted by 1 mg/l aviation fuel F34 (upper chromatogram) and a blood sample which was contaminated by jet engine exhaust (of jet fuel F34, 70% full load,- lower chromatogram).

6 Conclusion

The results obtained so far by the new analytical system for examination of POL, combustion gases and other volatile substances have come up to the expectations and show that it is possible to achieve

- very good separation performances,
- very high sensitivities and
- mostly definite identifications of the individual components separated.

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DISCUSSION - PAPER NO. 33

H. Weyer (Question)

Fuel additives might be harmful to environmental impact of air traffic. Do you have detailed information on the chemical composition of fuel additives?

H. Krause (Response)

Fuel additives may be hazardous to the environment, particularly because most of them are set free in high altitudes. To my knowledge, however, the issue has not yet been dealt with in a scientific Paper. As to the kind and quantity of the additives, there is little information available. A survey of the theory and the compounds applied can be found in Ref. 3.

F.S. Knox (Question)

How are you going to prioritize the study of the new compounds you can now detect?

H. Krausse (Response)

At the present stage of the research work, it is too soon to determine priorities as to the compounds to be detected. At the moment we examine as many differently polluted samples as possible to find out which of the detectable compounds might be suitable as significant markers showing that jet gas or combustion fuel has been taken.

Use of Object Oriented Programming to Simulate Human Behavior in Emergency Evacuation of an Aircraft's Passenger Cabin

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1. SUMMARY

The paper presents an object-oriented framework to model human behavior under both certification and accident evacuations. The framework opens up a new area of analysis by proposing a paradigm for predicting human behavior. Object oriented programming lends itself to the modeling of complex systems by supporting a one-to-one correspondence with the physical world, and thus, eases the burden of model validation. Easing model validation is of particular importance when the real-system's environment is hazardous, and performing tests on the real-system is either impossible or not repeatable.

2. INTRODUCTION

New designs of passenger aircraft are required to show compliance with 14 Code of Federal Regulations, Part 25, Section 803, *Emergency Evacuation.* This requirement is frequently referred to as *The 90 Second Rule.* The manufacturer must show that with half of the available exits blocked, a full load of passengers can safely evacuate the aircraft into a darkened hanger in 90 second or less. This requirement provides a performance based test of the emergency evacuation system of an aircraft. It has been found that in many accidents, the passengers survive the impact but perish because they are overcome by smoke and fire while trying to evacuate [Marcus 1994].

This certification testing has proven to be quite stressful and costly to the manufacturer. Today's certification test costs an average of $2.3 million, involves over 4000 people, and requires three years of planning [Shook 1995]. Adding to the cost is the risk of injuries to the test subjects. Consequently, there has been increasing pressure to improve certification tests' safety, even if the resulting tests give up some realism [Marcus 1994]. There is one realism that certification tests have never incorporated: the dynamic environment of an aircraft cabin during an accident (i.e., fire and smoke).

Since requiring manufacturers to perform certification tests under actual accident conditions is ethically unacceptable, the need then exists to develop an evacuation model capable of simulating (i) various cabin configurations, (ii) the dynamic environment of fire, and (iii) passenger behavior. At issue is the ability to accurately predict human behavior. More specifically, the ability to simulate the physical and psychological effects fire and smoke have on human behavior and decision making.

Past evacuation models have taken an expert system/ rule-based approach to model human decision making and behavior during aircraft evacuations [Galea and Galsarsoro 1993, Schroeder and Tuttle 1991]. The authors present a new approach to modeling human behavior: object oriented programming.

Object oriented programming (OOP) has two inherent features:

(1) OOP lends itself to the modeling of complex systems by supporting modular construction.

(2) OOP yields a one-to-one correspondence with the physical world and thus, eases the burden of validation.

Validation is critical to the successful use of a model as a predictive tool and involves testing to ensure that the model accurately reflects the behavior of the real system. Easing model validation is of particular importance when the real-system's environment is hazardous.

Other benefits of an object-oriented approach to predicting human behavior are: (i) human behavior modeling will support and enhance certification tests, currently conducted with human subjects, since simulated tests lend themselves to statistical and predictive analysis, and (ii) human behavior modeling will assist in the investigation of aircraft accidents by providing a means to analyze how behavior influences passenger survivability. For example, human behavior modeling will allow investigations into the impact flight attendants and their behavior have on directing passengers.

The paper presents an object-oriented framework for modeling human behavior and decision making during aircraft evacuations. The remainder of the paper is organized as follows:

(1) Section 3, *Objectives*, outlines the goals for the human behavior model.

(2) Section 4, *Object Oriented Programming*, presents a brief overview of the object-oriented approach to programming, corresponding terminology, and recent

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results in modeling cognitive processes via an object-oriented approach.

(3) Section 5, *Proposed Framework*, is the proposed object-oriented framework for modeling human behavior during aircraft evacuations.

(4) Section 6, *Conclusions and Future Research*, provides an overview of the construct and outlines future work.

3. OBJECTIVES

The object-oriented framework of Section 5 is proposed to support the development of human behavior models for analyzing aircraft cabin evacuations, with the following objectives:

(1) The model must be capable of analyzing various aircraft cabin configurations without requiring changes to its source code.

(2) The model must run in real-time or near real-time.

(3) The model must be able to conduct simulations of both certification tests and accident evacuations.

(4) The model must consider relationships among passengers. For instance, the impact on the evacuation behavior of a mother traveling with an infant versus a passenger traveling alone, must be incorporated.

(5) The model must consider the impact a flight attendant's behavior has on passengers. This feature will allow *passenger management* to be explored, such as determining the optimal number of flight attendants per passenger load.

(6) The model must offer dynamic behavior as opposed to behavior that is fixed at the time of model execution. That is, the model must allow the behavioral characteristics of the passengers to change over time.

(7) The model must take into account the dynamic, toxic environment of fire and consider the physical as well as psychological effect of fire and smoke on human behavior.

(8) The model must support simulation output analysis, designs of experiments, and sensitivity analysis.

(9) The model must provide animation of the evacuations to support model validation and presentations.

4. OBJECT ORIENTED PROGRAMMING

The advantages of object oriented programming over traditional (procedural) programming are well documented [Cox 1986, Meyer 1987], as are the advantages of object oriented design and development [Jacobson 1991, Kamath et al. 1993, Wang and Fulton 1994, Nof 1994, Fishwick 1995]. The major advantage of this approach to modeling is the preservation and reusability of source code. Traditional design uses the functions the systems performs as its basis for software development; while the object-oriented approach uses objects the system manipulates as its foundation. Since functions are likely to fluctuate and objects tend to be stable, the object-oriented approach allows for modularity in design and maintains reusability of software. Reductions in software development cycles have been realized as a direct result of code reusability [Kamath et al. 1993].

The following are definitions and features of object oriented programming supporting the modular decomposition of the software and code reusability:

(1) *Inheritance* allows for base code reusability and the implementation of new objects from existing objects. All objects belong to a class, where classes are defined in a hierarchical tree structure with subclasses inheriting the procedures and data storage structures of their superclasses. For a biological system, man is a subclass of mammals, mammals is then a sub-class of vertebrate, etc.

(2) Items within a system are called *objects*. This classification allows for the separation of physical items from functionality. Objects are treated either as a *class* or an *instance* of a class. A class is the software module providing the complete definition (capabilities) of the members within a particular class. These definitions are obtained either by procedures and data stored directly within the class definition, or are inherited from other related classes. An instance of a class is a realization of the class having all of the capabilities provided in its class definition. That is, an instance represents the execution of a class. Continuing the example of a biological system, a man is an instance of the class mammals. Man then inherits the features of other related classes, such as a vertebrate and animals. Man is distinguished from other mammal instances, like whales, through man's class definition of reasoning capabilities.

(3) *Late binding* allows for delaying the process of joining procedures to the data on which they will operate until execution of the model. Traditional programming uses early binding where the procedures and their data are joined (hard coded) at the time of code construction. Delaying the binding allows data types to change during execution and, again, supports code reusability.

(4) *Encapsulation* allows internal class implementations to be modified without changing the relationships of the instances of classes to other objects. Encapsulation ensures that an object's definition is within an impenetrable boundary. That is, the data stored within an object is only accessible by the procedures of its defined class. Message passing, as defined below, is a direct consequence of encapsulation.

(5) For one object to interact or affect the internal condition of another object, the requesting object must send a message asking the second object's procedures to execute the request. This is called *message passing*. Sending a message to an object invokes the same-named *method* (execution of code/routine/procedure) to be carried out by that object. Methods may either be inherited or are within an instance. Groups of similar methods are called *protocols.*

(6) The capability of different objects to respond to the same message in the appropriate manner is called *polymorphism*. That is, the message initiates different behaviors in various objects, even though the same message is sent.

Behavior is defined as the action an object takes when a message is received and when the object's behavior is influenced by its past behavior, then the object is said to have a *state* [Bourne 1992]. For an object to achieve a state, both class and instance (internal) variables must be defined. Class variables are common to all instances of a class, while internal variables define the state for a particular instance.

It was not until the 1980's when the works of King and Fisher [1986], Thomasma and Ulgen [1988], Adiga [1989], Mize et al. [1989], and Ulgen et al. [1989] showed that the underlying concepts of object oriented programming could be extended to simulation modeling.

Recent work has involved designing and developing an object-oriented simulation environment for manufacturing systems [Tretheway and Court 1995]. The approach was to model the physical and information/decision components of the manufacturing environment separately by using a five-level structured hierarchy of subsystems with the Smalltalk-80 language [Goldberg and Robson 1989]. A set theoretic formalism, first proposed by Karacal [1990], was used to support this separation.

There are many similarities between modeling manufacturing environments and modeling human behavior, such as:

(1) both systems are physical, yet information/decision based environments,

(2) both systems use complex decision-making heuristics and structures to control various operations (behavior),

(3) both are subject to the same problems associated with decision making: decisions can only be based on information that is currently available, although it may be incomplete or inaccurate,

(4) a passenger (like a decision maker within a manufacturing environment) will use heuristics, personal experience, and rules to arrive at control (behavior) decisions, and,

(5) as manufacturing systems are designed to achieve different goals and objectives yielding different levels of performance; humans are motivated and driven by different preferences and motivations, yielding different behaviors.

However, if the formalism for simulating manufacturing environments is followed, the objective of having the model run at real-time or near real-time will not be met.

In 1988, Burns and Morgenson [1988] published a construct for simulating systems involving endogenous decision making. Their work proposes describing the system in terms of a *suite of actor classes* (collection of object classes) whose endogenous decisions impact the performance and behavior of the system. They suggest a model where all actors, including pseudo-actors (environment), follow an actor-centered description (Figure 1). Each actor class requires data structures (assets, attributes and vulnerabilities) and methods (cognitive and physical capabilities), described as follows:

(1) *Assets* are discernible characteristics and *attributes* are descriptive characteristics. The actor's own assets and attributes comprise the *actual state*, while the *perceived state* is the actor's perception of its surroundings (the environment and other actors). The state of the actor is the combined data structures of the actual and perceived state. This state data is the input to the *cognitive inference engine* of the actor.

(2) The actor can physically move (*transfer*) or change (*transform*). Transformation takes place by modifying the actor's assets/attributes. *Vulnerabilities* represent degradation to the actor's capabilities via the reduction or destruction of the actor's assets.

(3) An action space for cognitive capabilities and activities describes the decision set and state of each actor. A *cognitive event* (decision) is capable of (i) delaying decisions, (ii) invoking physical activity, and (iii) changing the action space. By delaying decisions and changing the action space, an actor then has the ability to "change its mind" (non-monotonic reasoning).

Notice that the actor-centered description proposed by Burns and Morgenson [1988] is not a pure object-oriented paradigm, since knowledge bases (production rules and heuristics) and inference engines are utilized for achieving cognitive activity. Then adopting this approach would

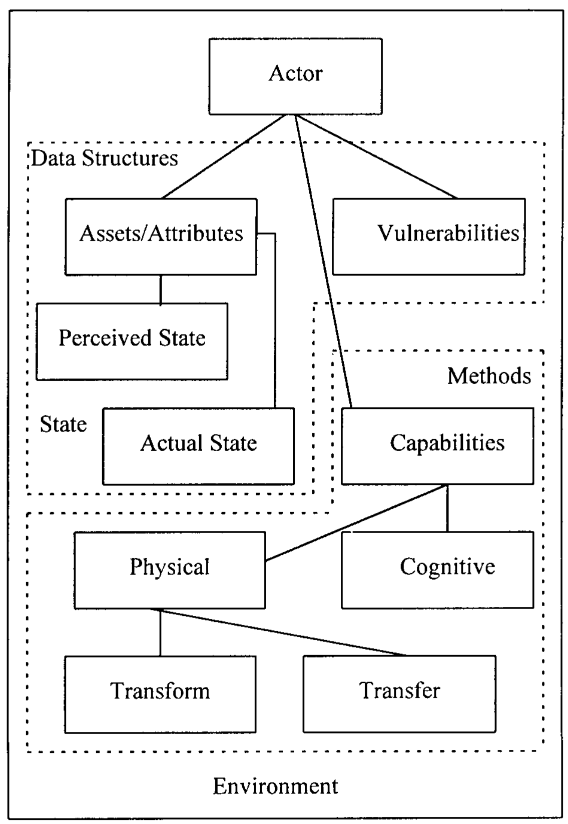


Figure 1: Actor-Centered Description
Source: Burns and Morgenson [1988] {modified}

equate to developing data, knowledge, and method structures for each actor (passenger) and pseudo-actor (environment). Thus the objective of supporting real-time simulation may not be met.

The proposed framework of Section 5 modifies the actor-centered description by avoiding the incorporation of knowledge bases and inferences via a pure object oriented paradigm. By maintaining a pure object oriented approach, it is expected that all of the objectives for the human behavior model (outlined in Section 3) will be achieved.

5. FRAMEWORK

The proposed framework for modeling human behavior is to adopt the actor-centered description of Burns and Morgenson [1988] but avoid the incorporation of knowledge bases and inference engines. This is achieved by allowing the actors to obtain their data and functions by copying other objects or parts of objects. This construct supports the need to have (i) a varied passenger and crew profile, (ii) a wide variety of aircraft cabin configurations, and (iii) the capability of simulating various hazardous environmental conditions.

An overview of the system is presented in Figure 2. The system is described below:

(1) The user is responsible for constructing a *passenger scenario module*, or choosing a system generated scenario. The passenger scenario includes all of the physical characteristics of the passengers and crew members (age, sex, height, weight, etc.), relationships between passengers (husband, wife, father, etc.) and those passengers identified as traveling together.

(2) The *layout module* is used to assign passengers and crew members to their seats and generate cabin configurations (number of rows, number and types of exits, locations of exits, aisle widths, etc.). The user has the option of using pre-existing cabin configurations, as well as the capability of generating new configurations. The user also has the option of pre-assigning the exits passengers and crew members use to evacuate the aircraft. Operable and blocked exits are also identified in this module.

(3) The *cabin environment module* is the vehicle to simulate accident/hazardous conditions. For example, the user has the option of invoking a pre-set fire with a known location and any ensuing toxicity or smoke. To run a certification test simulation the user would choose not to initiate this module.

(4) When the input to the three modules is complete, the system compiles the data and generates the various *actors* and *pseudo-actors*. For each passenger and crew member an actor object is created. The *fire, smoke,* and *toxicity* objects are pseudo-actors. For certification simulations these objects are not generated. Pre-existing objects are the *coordinate, navigate, advancement, synchronizer, panic,* and *responsibility* objects. The *synchronizer* object coordinates the objects and runs the simulation.

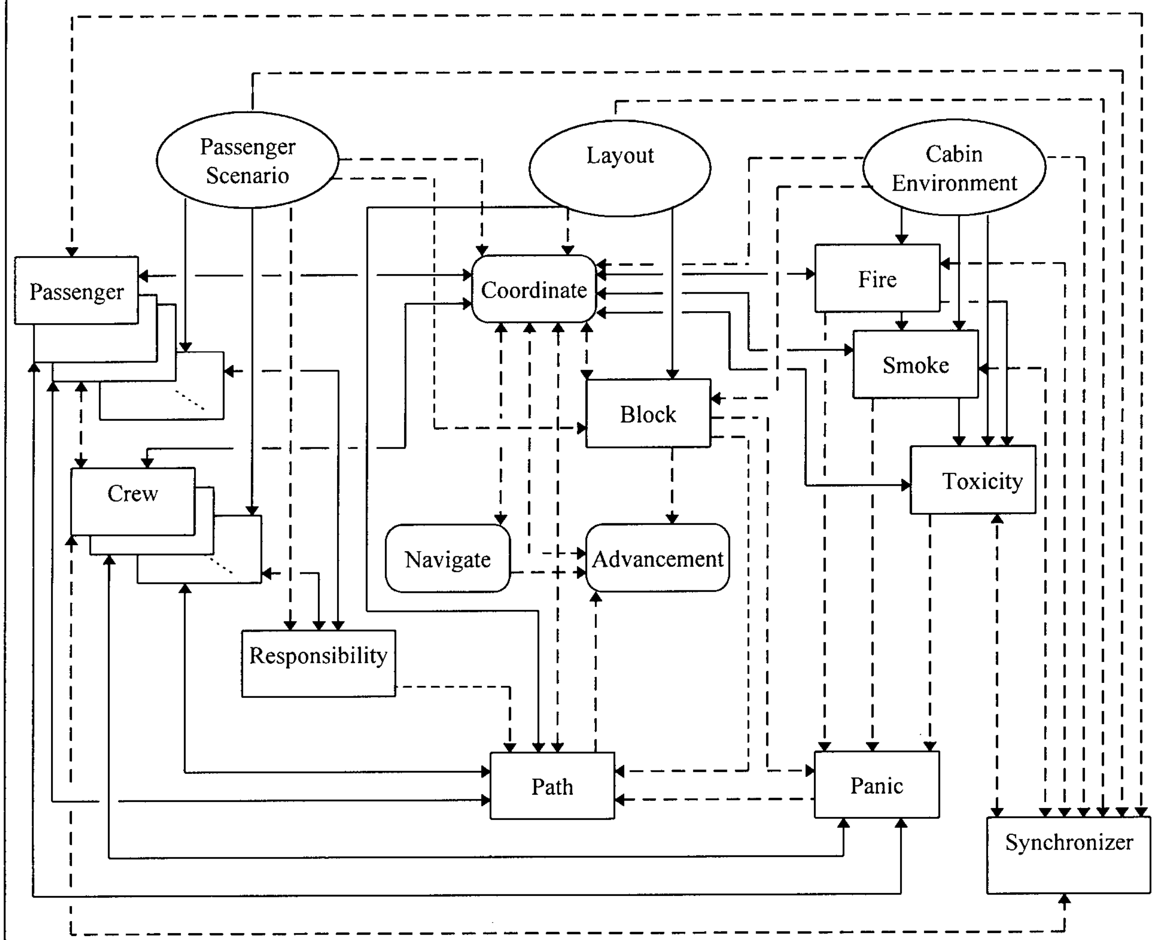
The coordinate, navigate, and advancement objects are copied into each of the actors and pseudo-actors. This construct avoids the need for developing knowledge bases and inference engines for each type of actor or pseudo-actor generated. The coordinate object receives the data input by the user and generates a map of the aircraft cabin. The passenger, crew, fire, smoke, and toxicity objects copy the coordinate functions of the coordinate object, and thus, are able to store and update their positions and distances from other objects. The navigate object is also copied into each actor object; and if applicable, the fire, smoke, and toxicity objects. The navigate functions allow the actors and pseudo-actors the capability of choosing headings (direction) for movement. The path object is called upon to generate possible paths for the actors and pseudo-actors, (fire, smoke, and toxicity) based on their positions, headings, and cognitive abilities to access the environment. The advancement object functions are used to move the actors and pseudo-actors to their requested positions. Data from the block object is used to keep actors and pseudo-actors from moving into inaccessible positions. The block data types consist of architectural (seats, walls, etc.), human (passenger and crew), and environmental (fire, smoke, and toxicity.) obstacles.

How 'capable' the actor is at using the coordinate, navigate, and advancement objects depends on its physical and cognitive capability objects. For example, the possible paths an object can construct and how many times a new path is generated, depends not only on how often the path object is called upon, but is a function of the actor's actual and perceived states. Thus, path generation is a function of the actor's (i) immediate environment (fire, smoke and toxicity levels), (ii) ability to access its current path and blockages, (iii) time spent in hazardous environments, and (iv) the type of evacuation being performed (certification or emergency).

The panic object directly influences the actor's ability to reason and react. Again, the call to the panic object will depend on the actual and perceived state of the actor and thus, is a function of the actor's capabilities.

The responsibility object is used to bind objects together. This is one of the vehicles used to establish a psychological profile for each actor, as well as a means to distinguish flight attendants and crew members from passengers. A flight attendant is expected to assist and direct passengers during an evacuation. In this paradigm, a flight attendant actor has access to the internal data of other objects. This is achieved in object oriented programming by designating objects as *friends* to other objects. Friend type objects also include passengers traveling together. The amount of internal data sharing depends on the relationship type and the amount of responsibility an actor has toward another actor.

The construct supports pre-defined biological hierarchies but allows distinction between objects within the same biological class. For example, although females have



KEY			
Symbol	Definition	Symbol	Definition
	User Module	⟶	Object Generation
	Object	- - -→	Data
	Copied Objects	⟷	Method/Function

Figure 2: Object-Oriented Framework for Human Behavior Model

many similar physical characteristics they do not have the same physical capabilities; likewise, they do not have the same cognitive reasoning abilities. Thus a distinction based on technical knowledge can be made between a female passenger and a female flight attendant. That distinction is incorporated through the ability to copy the coordinate, navigate, and advancement objects. The flight attendant is expected to have knowledge of the aircraft's configuration and therefore, has more access to the functions and data of the aforementioned objects then an average passenger. Also consider a female passenger traveling alone versus one traveling with an infant. The mother is bound to her child and therefore, would be expected to ensure that the child is evacuated safely. In the construct, when the mother actor is generated a copy of the bonding function from the responsibility object is copied into the *mother actor*. The mother actor is now tied to her *child actor* where the child's state is input to the cognitive object of the mother actor.

6. CONCLUSIONS AND FUTURE RESEARCH

The construct presented is an object oriented approach to modeling human behavior and decision making during aircraft evacuations. The construct alters the actor-centered

description of Burns and Morgenson [1988] by allowing objects to copy other objects for function execution. The ability to copy objects or parts of objects is the mechanism for actors to carry out cognitive and physical activities and thus, avoids the need for inference engines and knowledge bases.

Actors are capable of carrying out non-monotonic reasoning by repeatedly copying other object functions when deemed necessary by the actor. The number of times the copying can be carried out, the function that is actually copied, and the action that is taken by the actor (including no action at all), are all dependent on the actor's own cognitive and physical capabilities.

The construct also provides a means to study (i) the debilitating effects fire, smoke, and toxicity have aircraft evacuations, (ii) passenger management issues, and (iii) bonding.

The construct is currently being implemented at the University of Oklahoma's School of Industrial Engineering. The human behavior study is at the object and user module development stage, with validation being performed against certification test data. The study is also identifying the physical and psychological parameters most influential to passenger survivability [Jayarama and Court 1995]. A preliminary set of parameters is currently being incorporated into the model.

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DISCUSSION - PAPER NO. 34

A. Mulder (Question)

1) Is there a difference in behaviour of people in an environment of an aircraft, ship, building, etc...?

2) Is there a difference between the behaviour of a mother and her child and a father and his child?

M. Court - Author/Speaker (Response)

1) The model is specifically geared towards aircraft evacuations; however I would suspect that the same type of behaviour would be exhibited, e.g., panic, pushing, jumping, etc..

2) We have not investigated father -vs- mother, per se. We would expect a parent to be interested in saving the child first (regardless of the sex of the parent). I would expect the capability of the father to complete this task to be (physically) better than that of the mother, when based on strength.

P. Macey (Question)

Many of the processes you describe appear to be suited to analysis with 'fuzzy logic' methods. Have you evaluated the use of such an approach and, if so, what were your conclusions?

M. Court - Author/Speaker (Response)

We are aware of 'fuzzy logic' methods and we have not considered this for an approach (as yet) since we wanted to stay strictly 'object-oriented'. However, we may investigate 'fuzzy logic' for object functions and methods.

Passenger Protection and Behaviour

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1. INTRODUCTION

The world-wide accident statistics indicate that the number of accidents has decreased over the last two decades (Ref.1). Unfortunately, the dramatic reduction in the overall accident rate was accompanied by a less dramatic reduction in the fatality rate of those onboard an aircraft which is involved in an accident (Ref.2). Nevertheless, recent analyses conducted by the FAA have indicated that fire has become less of a risk in survivable accidents. In the early 1980s, FAA attributed 40 percent of fatalities in survivable accidents to fire effects. A review of US airline accidents that occurred between 1985 and 1991 showed that approximately 10 percent of fatalities were related to fire (Ref.3).

Whilst no two accidents can ever be the same, it is possible to learn from the similarities and differences between the causes of the accidents, their location and the environmental conditions present, the types of passengers onboard and their responses to the emergency. For instance, there were many similarities between the accident which occurred at Manchester in 1985 and the one which occurred at Calgary in 1984, in that they were both caused by an engine fire at take off. However, they differed in one important respect, namely that at Manchester there were 55 fatalities whereas in Calgary everyone survived. We know that in some aircraft accidents everyone files out of the plane in a rapid although orderly manner. For example, in the evacuation of a British Airways 747 at Los Angeles in 1987, as a result of a bomb scare. In other accidents however, the orderly process is not adhered to and confusion in the cabin can lead to blockages in the aisles and at exits, with a consequent loss of life. For example, in the accident which occurred at Los Angeles Airport in 1991 where, as at Manchester in 1985, the overwing exit became blocked by passengers desperately trying to get out of the aircraft.

From the reports of a number of accidents it is possible to build up a picture of the exits typically used by passengers who survive an emergency where there is smoke and fire, as can happen following crash landing (Figure 1).

From this we know:

a. that some passengers exit by their nearest door, as would be expected.

b. that other passengers do not exit by their nearest available door but travel for considerable distances along the cabin, e.g. extreme cases of back to front. Why and in which circumstances do they choose to do this?

c. that other passengers apparently near exits, do not survive. Do they panic and freeze, give up, get crushed by other people from behind or around, do they have their seat backs pushed onto them?

d. we also know that blockage can occur in the aisles and at exits in some accidents, when this does not occur in evacuation demonstrations for certifications.

There are in fact a great many questions which as yet we are not able to answer about the behaviour of people in emergencies, including the important question of why in some accidents the passengers evacuate in an orderly manner, and in other accidents the behaviour is disorderly.

It is suggested that one of the primary reasons for the differences in behaviour, between the orderly and disorderly situations must rest with the individual motivation of the passengers. In some accidents as in the aircraft certification evacuations, all of the passengers assume that the objective is to get everyone out of the aircraft as quickly as possible, and they therefore all work collaboratively. In other emergencies, however, the motivation of individual passengers may be very different, especially in the presence of smoke and fire. In a situation where an immediate threat to life is perceived, rather than all passengers being motivated to help each other, the main objective which will govern their behaviour will be survival for themselves, and in some instances, members of their family. In this situation when the primary survival instinct takes over, people do not work collaboratively. The evacuation can become very disorganised, with some individuals competing to get through the exits. The behaviour observed in the accident which occurred at Manchester, and other accidents including the fire at the Bradford City football stadium, and the Zeebrugge ferry disaster, supports this theory

If it is accepted that in life threatening situations such as those involving smoke and fire, passenger behaviour can become highly charged and extreme, the question to be asked is how can this behaviour be controlled.

Interestingly an important insight into this problem was obtained from investigators following the accident which happened at the J F Kennedy Airport in New York in 1992 (Ref. 4) The accident involved a widebodied aircraft which caught fire and just as in the accidents at Manchester and Los Angeles, there was approximately two minutes with half of the exits operational. In this accident all of the passengers successfully evacuated the aircraft. Why did all of the passengers survive in this accident when in equivalent circumstances with half the exits operational for two minutes passengers died at Manchester and Los Angeles.

Paper presented at the PEP Symposium on "Aircraft Fire Safety", held in Dresden, Germany, 14-17 October 1996, and published in CP-587.

Two reasons have been proposed. The first is that as there were no overwing exits on the jumbo aircraft the possibility of these becoming blocked had been eliminated. The second reason is that although the aircraft had originally been certificated for six cabin crew, because of the company service requirement the aircraft was being flown with nine cabin crew. Fortunately on the flight, five additional cabin crew were flying supernumerary and they assisted with the evacuation of the passengers. Thus rather than the certificated crew of six cabin staff the passenger evacuation was assisted by thirteen cabin staff. This fact clearly indicated the vital role played by cabin staff in an emergency.

In 1995 Cranfield University was requested by the UK Civil Aviation Authority (CAA) and the Federal Aviation Administration (FAA) of the United States of America to conduct a programme of research to explore the influence of Cabin Crew Behaviour on the evacuation of passengers in an aircraft emergency.

The factors which were identified included whether a flight attendant was present at the exit, and the influence of assertive and non-assertive behaviour by flight attendants on evacuation behaviour and exit rates. These factors were investigated by conducting evacuations with either one, two or no flight attendants at a single floor level exit, and with one, two or no flight attendants supervising at two floor level exits. the objective of the test series was to determine whether the performance and number of flight attendants would influence the evacuation process.

2. METHODOLOGY

In the assessment of any facilities or procedures to be used by members of the public in an emergency, the major dilemma is how to introduce a realistic test without actually putting people at serious mental or physical risk. Researchers in the UK (at Cranfield) have pioneered a technique which the regulators believe has the potential to provide both the behavioural and statistical data required for the assessment of design options or safety procedures for use in emergency evacuations, which maximises the degree of realism acceptable in test conditions (Ref.5). This technique (competitive) was used for the evacuation testing as it was considered to produce the best possible simulation of the behaviour of passengers which can occur in an emergency situation which is perceived to be immediately life threatening. In order to simulate the urgency which can lead to passengers pushing towards exits in an attempt to evacuate quickly, incentive payments of £5 were offered to 75% of the volunteers to exit the airframe.

A new technique (collaborative) was developed which was designed to produce a simulation of the behaviour of passengers which occurs when an emergency evacuation is required but the passengers do not perceive an immediate life threat. This technique involved offering incentive payments to all of the volunteers if they all successfully evacuated from the airframe in less than 90 seconds.

The tests were conducted from a narrow bodied 737 aircraft simulator configured to the current regulations (with a Type I passenger loading door on the port side (L1) and a Type I service door on the starboard side (R1) which were typical of those used on actual aircraft. See Appendix A for details. Each test involved the evacuation of a complement of 60 volunteer passengers seated in the forward section of the simulator. The volunteers evacuated down specially constructed slides.

Previous testing programmes at Cranfield had demonstrated that in order to maximise the opportunities for data collection each individual group of volunteers could successfully take part in up to four evacuations in one session. Since the behaviour of flight attendants on the first evacuation was likely to determine the behaviour of volunteers on that and any subsequent evacuations, the following groups were used for the tests:

Ia. Four independent groups of volunteers were tested with two assertive flight attendants. Each group completed tests A, B, C and D described below. (Assertive behaviour included calling volunteers to exits and actively pushing them through exits as rapidly as possible in a highly active but non-aggressive manner).

Ib. Four independent groups of volunteers were tested with one assertive flight attendant. Each group completed tests A, B, C and D described below. (Assertive behaviour included calling volunteers to exits and actively pushing them through exits as rapidly as possible in a highly active but non-aggressive manner).

IIa Four independent groups of volunteers were tested with two non-assertive flight attendants. Each group performed tests A, B, C and D described below. (Non-assertive behaviour involved asking volunteers to come to exits and only giving physical assistance when someone was in danger of falling).

III Four independent groups of volunteers tested with no flight attendants to assist the evacuation. Each group performed tests A, B, C and D described below.

Each independent group performed each of the following four evacuations in a counterbalanced order:

A. The LI door only operational at the front of the cabin, and bonus payments to the first 75% of volunteers to evacuate.

B. The LI and RI doors operational at the front of the cabin, and bonus payments to the first 75% of volunteers to evacuate.

C. The LI only at the front of the cabin operational, and bonus payments made to all of the volunteers if the evacuation took less than 90 seconds.

D. The LI and RI doors at the front of the cabin operational, and bonus payments made to all of the volunteers if the evacuation took less than 90 seconds.

In all of the tests the flight attendants operated the exits. In the conditions when no flight attendants assisted with the evacuation the flight attendants opened the exits and immediately evacuated down the slides ahead of the passengers.

The volunteers were recruited by local advertising and told that they would be paid a £10 attendance fee after they had completed

four evacuations. Although the volunteers were told that they would be required to take part in evacuation testing from a simulator, they were not given any information about the procedures or configurations under review, or the order in which the evacuations were to be performed. The volunteers were instructed that their task was to evacuate the aircraft as quickly as possible once the exits had been opened by the flight attendants. On the first two evacuations (competitive) a £5 bonus was paid to the first 75% of the volunteers to pass through the exits which were used on each evacuation. On the third and fourth evacuations (collaborative) a £5 bonus payment was made to all of the volunteers if they all completed both of these evacuations in less than 90 seconds.

The bonus payments were made immediately after each evacuation. Seating plans were developed for the volunteers for the four successive evacuations from the aircraft, which gave every volunteer an equal chance of receiving the monetary incentive. Volunteers were not allowed to take part in a test session more than once.

The safety of volunteers was an important consideration. To this end, only volunteers who claimed to be reasonably fit and were between the ages of 20-50 were recruited. On arrival all volunteers were given a medical examination. They were also asked to complete a questionnaire indicating that, (i) they had fully understood the purpose of the tests, (ii) the medical information which they had supplied was correct and (iii) that they were satisfied with the insurance cover. A doctor and members of the airfield fire service were present to assist passengers at the bottom of the slides. A system of alarms was available to stop any evacuations should a real emergency occur or when there was concern for the safety of any volunteer.

In order to introduce as much realism as possible, on their arrival at the simulator the volunteers were met by members of the research team trained and dressed as flight attendants. After boarding, they were given a standard pre-flight briefing by the flight attendants, they then heard a sound recording of an aircraft starting up and taxiing to a runway. This sequence of recording was varied but included the simulated sounds of an aborted take-off and a period of silence, in which time the pilots were supposedly shutting down engines and liaising with the flight attendants. The variation ensured that the volunteers could not anticipate the precise time at which the call to evacuate would be given. On the command 'Undo your seatbelts and get out', the appropriate exits were opened and the volunteers evacuated down the slides. Airfield fire officers were located at the bottom of each slide to assist the volunteers to move away quickly. Video cameras with time bases were used for the recording of the behaviour of the volunteers and the evacuation times. The data collection was designed to provide the information required for the development of computer based egress models.

After each evacuation all of the volunteers were required to complete a questionnaire to determine the extent to which they felt the cabin crew had aided their escape. Demographic information relating to each volunteer's age, sex, height and weight and behavioural traits was also collected. Before volunteers left the site they were given a debriefing in which they were reminded of the safety of air travel and advised that they should get back in touch with Cranfield if they experienced any physical or emotional problems as a result of participating in the evacuations.

3. RESULTS

The test series involved 16 test days with independent groups of volunteers. The numbers on any test day ranged between 42 and 60 with the average being 55. The participants were 64% male and 36% female. Each group performed four evacuations. A number of evacuations were halted because the conditions in the cabin became so extreme that there was a risk of volunteers becoming injured. These occurred on 0 evacuations with two assertive flight attendants, 2 evacuations with one assertive flight attendant, 1 evacuation with two non-assertive flight attendants and 2 evacuations with no flight attendants to assist the evacuations (see Table 1). Thus a total of 59 evacuations were completed. During the series of trials a few volunteers found they had sustained minor bruises whilst evacuating the aircraft and friction burns when using the evacuation slides. One volunteer unfortunately fractured her ankle whilst jumping onto the slide.

In the competitive evacuations when bonus payments were made to the first 75% to evacuate the male volunteers on average obtained 1.6 bonuses out of a possible 2 whereas the female volunteers obtained only 1.4 bonuses. This difference is statistically significant ($t = 3.39$ df 1, 336, $p < 0.001$). Younger volunteers obtained significantly more bonuses than older volunteers ($F = 6.25$ df 2, 483, $p < 0.004$). These data can be seen in Tables 2 and 3.

Passenger evacuation times through the exits were obtained from video recordings. The evacuation rates (the average time for each participant to evacuate) were calculated using the time of the last bonus receiving participant to reach the ground. Since bonus payments were only available to the first 75% of volunteers and there were approximately 60 volunteers on the aircraft it was assumed that some of the volunteers coming out after this point would not be competing. For this reason their data was not included in the analysis.

In the competitive evacuations the results clearly indicated the importance of having flight attendants who adopt assertive behaviour (see Table 3). As the mean evacuation rates demonstrated, statistical treatment of the data indicated that the presence of assertive flight attendants significantly increased the speed of the evacuation ($F = 14.72$, df 2,15 $p<0.0001$). The small differences between the egress times in evacuations with non-assertive flight attendants and no flight attendants were not significant.

The mean evacuation rates also suggested that in evacuations where there were two assertive flight attendants to assist the volunteers can be faster than those where only one assertive flight attendant is present.

As expected the evacuations all took place more quickly when two exits were available rather than when only one exit was operational ($F=63.68$, df 1,19 $p<0.0001$). Total times for each exit, when both exits were available, were not significantly different.

As in the competitive evacuations, the mean evacuation rates for the co-operative evacuations indicated that the presence of assertive flight attendants significantly increased the evacuation rate ($F = 13.98$, df 2,18, $p<0.0001$).

4. DISCUSSION

Prior to the initiation of the research programme, tests involving members of the public evacuating from an airframe down escape slides using incentive payments had not been conducted. There was concern that the increased motivation induced by the incentive payments would lead to serious injuries among the volunteers. It proved to be possible to conduct tests involving both the competitive and collaborative bonus payment methodology without causing an unacceptable level of injury to the volunteers. Thus the research has demonstrated that the techniques can be used to simulate the two types of behaviour which can occur in an aircraft emergency in which an evacuation is required.

The findings that males tended to obtain more bonuses than females and that younger volunteers were more successful than older volunteers is a reflection of the similarity between the behaviour in this methodology and in actual accidents where fit young males have statistically the greatest probability of survival.

The fact that the evacuation rates for both the competitive and collaborative tests were faster when assertive flight attendants were present clearly indicates that it is essential that all flight attendants are trained to adopt assertive behaviour in an emergency.

It is not surprising that in all of the conditions the mean evacuation times were faster with two rather than one flight attendant. However it is interesting that this advantage of having two flight attendants is greatest when there is only one exit operational and the individual volunteers are highly motivated. In the situation with only one door operational one of the attendants could assist passengers onto the slide while the other controlled the progress of volunteers through the bulkhead in an attempt to prevent the blockages which can occur and which can reduce the speed of the evacuation. When two exits were operational the flight attendants were less able to perform this function as they were each required at the exits to assist volunteers onto the slides.

5. CONCLUSION

1. The results from the programme of evacuations involving both competitive and co-operative behaviour between passengers suggested that the behaviour and number of cabin crew significantly influenced the speed at which passengers are able to evacuate. When two assertive cabin crew were present passengers were able to evacuate the aircraft more quickly than when assisted by one assertive cabin crew. The evacuations involving the non-assertive or no cabin crew were significantly slower than those with assertive cabin crew.

2. The results from a comparison of the video data from the competitive and co-operative evacuations indicated that the two research techniques which were used can together produce the range of behaviours seen in accidents. The competitive tests provided an effective simulation of emergency behaviour when conditions in the cabin are perceived to be life threatening and the co-operative produced the behaviour which can occur in precautionary evacuations and certification demonstrations.

3. The results suggested that assertive cabin crew behaviour is essential. This will need to be reflected in current training of cabin crew and may have implications for cabin crew selection in the future.

4. It was found that cabin crew played a positive role in managing the passengers during evacuations from the simulator.

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TABLE 1 **Number of Evacuations Undertaken**

Cabin Crew Type	Number of Evacuations		
	1 Door	2 Doors	Total
2 Assertive	8	8	16
1 Assertive	8	6	14
2 Non-Assertive	8	7	15
None	7	7	14

TABLE 2 **Number of Bonuses for Males and Females**

	Mean number of bonuses	S.D.
Male	1.58	0.53
Female	1.38	0.58

TABLE 3 **Number of Bonuses and Age**

Age	Mean number of bonuses	S.D.
20-23	1.58	0.55
31-40	1.48	0.56
41-50	1.33	0.53

TABLE 4 **Competitive Evacuations - Mean evacuation rates for each participant (time in seconds)**

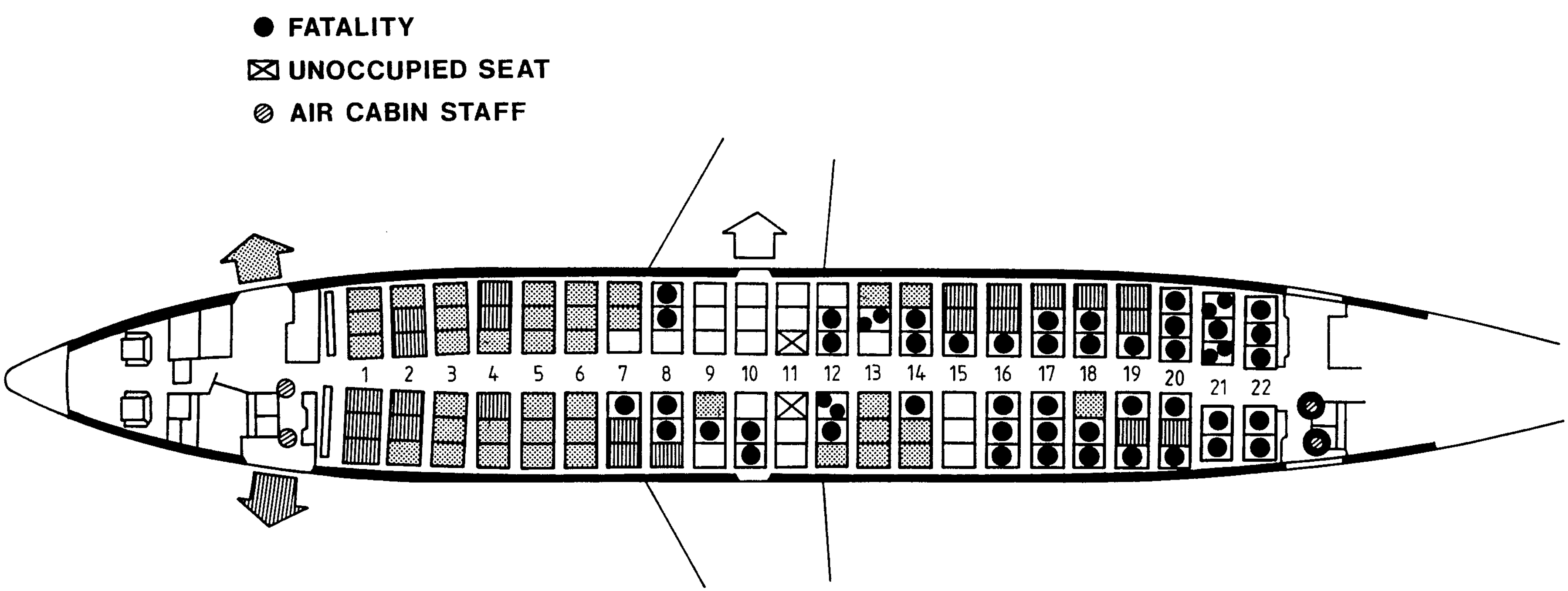
Attendants	1 door		E/N	2 door		E/N
	Mean	SD		Mean	SD	
2 Assertive	1.26	0.13	4	0.82	0.03	4
1 Assertive	1.40	0.46	4	0.81	0.09	2
2 Non-Assertive	1.72	0.17	4	0.92	0.04	3
None	1.89	0.26	3	0.94	0.04	3

TABLE 5 **Co-operative Evacuations - Mean evacuation rates for each participant (time in seconds)**

Attendants	1 door		E/N	2 door		E/N
	Mean	SD		Mean	SD	
2 Assertive	1.27	0.14	4	0.77	0.05	4
1 Assertive	1.33	0.23	4	0.80	0.10	4
2 Non-Assertive	1.69	0.17	4	0.90	0.09	4
None	1.61	0.10	4	0.91	0.08	4

FIGURE 1

SIMULATION OF SURVIVOR ESCAPE DOOR AND SEATING FATALITIES



THE ROLE OF EVACUATION MODELLING IN THE DEVELOPMENT OF SAFER AIR TRAVEL.

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1. SUMMARY

Computer based mathematical models describing the aircraft evacuation process have a vital role to play in the design and development of safer aircraft, in the implementation of safer and more rigorous certification criteria and in post mortuum accident investigation. As the risk of personal injury and costs involved in performing large-scale evacuation experiments for the next generation 'Ultra High Capacity Aircraft' (UHCA) are expected to be high, the development and use of these evacuation modelling tools may become essential if these aircraft are to prove a viable reality. In this paper the capabilities and limitations of the air-EXODUS evacuation model are described. Its successful application to the prediction of a recent certification trial, prior to the actual trial taking place, is described. Also described is a newly defined parameter known as OPS which can be used as a measure of evacuation trial optimality. Finally, the data requirements of aircraft evacuation models is discussed along with several projects currently underway at the University of Greenwich designed to obtain this data. Included in this discussion is a description of the AASK - Aircraft Accident Statistics and Knowledge - data base which contains detailed information from aircraft accident survivors.

2. INTRODUCTION

When modifying an existing aircraft or designing a new aircraft, how do we ensure that the proposed design is safe, and how we demonstrate that it is safe? As a real but extreme example of this problem consider the proposed next generation UHCA.

Designs currently being considered are capable of carrying 800+ passengers with interiors consisting of two aisles and possessing two full length passenger decks. Questions concerning seating arrangement; design of recreational space; number and location of internal staircases; number, location and type of exits; number of required flight attendants and flight attendant emergency procedures are just some of the issues that need to be addressed. The quantum leap in passenger capacity being suggested should also challenge some of our preconceptions in equipment design and operating procedures. For instance, in order to efficiently complete an evacuation, will it be necessary to extend emergency procedures to the marshalling of those passengers already on the ground? Should evacuation procedures allow passengers to travel between decks before exiting the aircraft? Do we need to consider a new type of exit design?

Quite apart from questions of emergency evacuation, issues concerning the appropriateness of proposed designs in allowing the rapid and efficient movement of passengers during boarding and disembarkation are a further essential design consideration. Furthermore, these requirements may potentially be in conflict with the requirements for emergency egress. Ultimately, the practical limits on passenger capacity are not based on technological constraints concerned with aircraft aerodynamics but on the ability to evacuate the entire complement of passengers within agreed safety limits.

Under current regulations set by national and international certification authorities, aircraft manufacturers must demonstrate that new aircraft designs or seating configurations will allow a full load of passengers and crew to safely evacuate from the aircraft within 90 seconds. The accepted way of demonstrating this capability is to perform a full-scale trial using the passenger compartment under question and an appropriate mix of passengers. Since 1969 more than 20 full-scale evacuation certification demonstrations have been performed involving over 7000 volunteers [1].

The difficulties with this approach is that it poses considerable ethical, practical and financial problems which bring into question the value of their overall contribution to passenger safety. The ethical problems concern the threat of injury to the participants and the lack of realism inherent in the 90 second evacuation scenario. Between 1972 and 1991 a total of 378 volunteers (or 6% of participates) sustained injuries ranging from cuts and bruises to broken bones [1]. During the October 1991 McDonnell Douglas evacuation certification trial for the MD-11, a female volunteer sustained injuries leading to permanent paralysis.

Furthermore, as volunteers are not subject to trauma or panic nor to the physical ramifications of a real emergency situation such as smoke, fire and debris, the certification trial provides limited information regarding the suitability of the cabin layout and design in the event of a real emergency. The Manchester disaster of 1985, in which 55 people lost their lives serves as a recent tragic example. The last passenger to escape from the burning B737 aircraft emerged 5.5 minutes after the aircraft stopped, while 15 years earlier during UK certification trials the entire load of passengers and crew managed to evacuate the aircraft in 75 seconds [2].

On a practical level, as only a single evacuation trial is necessary for certification requirements there can be limited confidence that the test - whether successful or not - truly represents the

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evacuation capability of the aircraft. In addition, from a design point of view, a single test does not provide sufficient information to arrange the cabin lay out for optimal evacuation efficiency nor can it match all the different configurations flown by all the potential carriers. Finally, each full-scale evacuation demonstration can be extremely expensive. For instance an evacuation trial from a wide-body aircraft costs in the vicinity of $US2 million [1]. While the cost may be small in comparison to development costs it remains a sizeable quantity.

Computer based egress/evacuation models have the potential of addressing all these shortfalls. Computer based mathematical models describing the aircraft evacuation process have a role to play in the design and development of safer aircraft and improved crew procedures, bringing safety matters to the design phase while the proposed aircraft is still on the drawing board. These models also have a role to play in the implementation of safer and more rigorous certification criteria. Finally, evacuation models can also be used to help optimise the efficient movement of passengers during loading and disembarkation.

If evacuation models are to fulfil their promise, they must address the configurational, environmental, behavioural and procedural aspects (see figure 1) of the evacuation process [3]. Configurational considerations are those generally covered by conventional methods and involve cabin layout, number of exits, exit width, travel distance etc. In the event of fire, environmental aspects need to be considered. These include the likely debilitating effects on the passengers of heat, toxic and irritant gases and the impact of increasing smoke density on travel speeds and way-finding abilities. Procedural aspects cover the actions of staff, passenger prior knowledge of the cabin, emergency signage etc. Finally, and possibly most importantly, the likely behavioural responses of the passengers must be considered. These include aspects such as the passengers initial response to the call to evacuate, likely travel directions, family/group interactions etc.

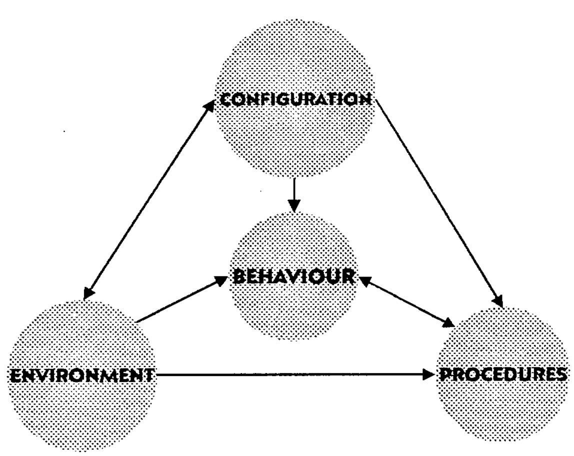

FIGURE 1: The Four Main Interacting Aspects To Be Considered In The Optimal Design Of An Enclosure For Evacuation.

The air-EXODUS evacuation model [4,5,6] attempts to address all four of the contributory aspects controlling the evacuation process. In order to understand how these components are brought together within an evacuation model and highlight their associated data requirements, a brief description of the air-EXODUS evacuation model follows.

3.0 THE air-EXODUS EVACUATION MODEL

3.1 EXODUS Overview.

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of individuals from complex structures. EXODUS was originally designed for use with aircraft. However, its modular format makes it ideally suited for adaptation to other types of environment. As a result its range of application has grown as has the number of specific EXODUS products. The EXODUS family of evacuation models currently consists of two distinct packages, building-EXODUS [7,8,9] and air-EXODUS.

building-EXODUS is designed for applications in the built environment and is suitable for application to high rise buildings, rail stations, airport terminals, etc. building-EXODUS can be used to demonstrate compliance with building codes and to evaluate the evacuation capabilities of all types of structures.

air-EXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90 second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation.

The EXODUS software is portable across platform types from PCs running the WINDOWS environment to UNIX WORKSTATIONS running under MOTIF. The minimum recommended computer platform comprises a 25 MHz 486 PC with 8 Mbytes of memory. Run on this platform a simulation of a wide-body aircraft evacuation involving 400 occupants requires approximately three minutes CPU time.

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. The model tracks the trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat, smoke and toxic gases. The EXODUS software has been written in C++ using Object Orientated techniques and rule-base software technology to control the simulation. Thus, the behaviour and movement of each individual is determined by a set of heuristics or rules.

3.2 air-EXODUS Submodels.

For additional flexibility these rules have been categorised into five interacting submodels, the OCCUPANT, MOVEMENT, BEHAVIOUR, TOXICITY and HAZARD submodels (see figure 2). These submodels operate on a region of space defined by the GEOMETRY of the enclosure.

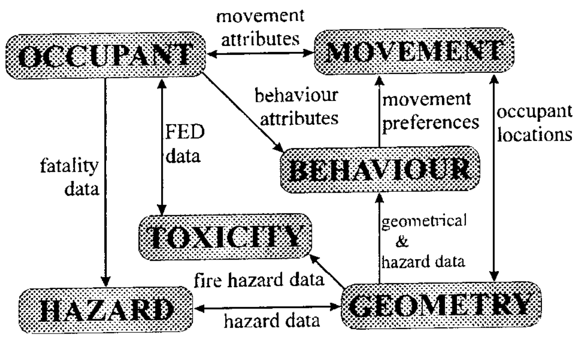

FIGURE 2: air-EXODUS Submodel Interaction.

3.2.1 Enclosure Description

Within air-EXODUS, the enclosure GEOMETRY is made up from two-dimensional grids. The GEOMETRY can be defined in several ways. It can be (i) read from a geometry library, (ii) constructed interactively using the tools provided or (iii) read from a CAD drawing using the DXF format. Internally the entire space of the geometry is covered in a mesh of nodes which are typically spaced at 0.5m intervals. Each node represents a region of space typically occupied by a single occupant. Nodes are linked to their nearest neighbours by a number of arcs, typically four or eight. Nodes which have distinguishing features may be assigned to special node classes for example, *aisle*, *stair*, *seat*, *door* etc. Occupants travelling over specific node types will be assigned attribute values appropriate for that node type, for example different maximum travel speeds and behavioural responses would be appropriate for an individual travelling over an aisle node as opposed to a stair node.

Associated with each node is a set of attributes which define the state of the node. These are, temperature (degree C), HCN (ppm), CO (ppm), CO_2 (%), oxygen depletion (%) and smoke concentration. For each of these variables, two values are stored, representing the value at head height and near floor level. air-EXODUS does not include a component for **predicting** the generation and spread of fire hazards but simply distributes the hazards generated by fire models.

Each node is also assigned an obstacle value which is a measure of the degree of difficulty in travelling over the node. A node representing an open space may have an obstacle value of one, while a node with debris may have a higher value of four for example.

3.2.2 The Occupant Submodel

The **OCCUPANT** submodel defines each individual as a collection of 20+ attributes which broadly fall into four categories, *physical* (such as age, weight, gender, agility etc), *psychological* (such as patience, drive etc), *positional* (such as distance travelled, PET etc) and *hazard effects* (such as FIN, $FICO_2$, FIH etc). These attributes have the dual purpose of defining each occupant as an individual and allowing their progress through the enclosure to be tracked. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other submodels.

3.2.3 The Movement Submodel

The **MOVEMENT** submodel is concerned with the physical movement of the occupants through the different terrain types. Its main function is to determine the appropriate travel speed for the terrain type, for example - leap speed for jumping over seat backs. In addition it also ensures that the occupant has the capability of performing the requested action, for example - checks if occupant agility is sufficient to allow travel over node with particular obstacle value. The direction of travel is determined by the behaviour submodel.

3.2.4 The Hazard Submodel

The **HAZARD** submodel controls the enclosure environment and allows the user to specify the specific *simulation scenario*. The environmental aspects comprise the spread of fire hazards CO_2, CO, HCN, O_2 depletion, heat and smoke. The values for these are set at two heights, head height and knee height. Although EXODUS contains no specific component to generate the fire hazards, it has the capability to use input from fire models [10] and experimental data. Scenario specific factors which are controlled by the Hazard model include aspects such as door opening/closing times.

3.2.5 The Toxicity Submodel

The **TOXICITY** submodel functions only when fire hazards are present. Its' function is to determine the effect of fire hazards upon the occupants.· The TOXICITY submodel currently models the effects of the narcotic fire gases, heat and smoke. The effect of the narcotic gases and heat are modelled using various Fractional Effective Dose (FED) models [11,12]. During a simulation smoke is considered to reduce an occupants egress capability by decreasing their travel speed. The decrease in travel speed is based on the work of Jin and Yamada [13]. Furthermore, at a critical smoke density the occupants are forced to crawl. When this occurs the occupants are exposed to the fire hazards located at the lower level.

3.2.6 The Behaviour Submodel

The **BEHAVIOUR** submodel determines an occupants response to the current prevailing situation. It is the most complex of the submodels. The behaviour submodel operates on two levels, *global* and *local*. The global behaviour provides an overall escape strategy for the occupants while the local behaviour governs the occupants' responses to their current situation. While attempting to implement the global strategy, an individuals behaviour can be significantly modified by the dictates of their local behaviour.

In the current implementation of EXODUS the global behaviour is fairly simple. This involves implementing an escape strategy which leads occupants to exit via their nearest

serviceable exit or the exit to which they have been directed to by cabin staff.

The second level of Behaviour Submodel function concerns the occupants' response to local situations. This includes such behaviour as determining the occupants initial response to the call to evacuate i.e. will the occupant react immediately or after a short period of time or display behavioural inaction, conflict resolution, overtaking and the selection of possible detouring routes. The local behaviour is determined by the occupants attributes and as certain behaviour rules (e.g. conflict resolution) are probabilistic in nature, the model is unlikely to produce identical results if a simulation is repeated. There are two operational regimes under which local behaviour rules function, these are known as, *EXTREME* and *NORMAL* behaviour. Under *NORMAL* behaviour conditions, the occupants will behave in an orderly manner and for the most part attempt to adhere to the global behaviour rules. This is the preferred mode of operation when attempting to simulate 90 second certification trials. Under *EXTREME* behaviour occupants are given a wider range of options such as jumping over seats, moving away from a exit, heading for an exit which is not necessarily their closest exit, etc. This is the preferred mode of operation when attempting to simulate realistic evacuation scenarios. Some of the local behaviour typically observed in air-EXODUS simulations will be discussed.

(i) Response time - this is a measure of the time an occupant requires before they have moved out of their seat. It can involve a representation of an individuals reaction time, time to release seat restraint and time to stand upright. An individuals response time is part of the occupant attribute parameter set.

(ii) Conflict resolution - when two or more occupants via for space (usually in crowds) conflicts arise which must be resolved. Conflict resolution is the procedure by which this occurs within air-EXODUS.

air-EXODUS utilises a fine network of nodes to describe an enclosure. Each node is intended to represent the smallest amount of free space available for occupancy, essentially it is the space that a single individual can occupy. Thus only one occupant can occupy a node at a time. However, the situation often arises where two or more occupants may wish to occupy a particular node. An example to illustrate this is shown in figure 3 where three occupants wish to occupy the same node, two occupants are attempting to enter the aisle from their seats, while a third occupant, already in the aisle, is attempting to proceed. The three occupants (labelled 1,2 and 3) are attempting to occupy the indicated node and thus a three-way conflict arises.

Given that the travel distances and speeds associated with each of the conflicting occupants are such that there is no clear winner, the outcome of such a conflict would depend on the *drive* psychological attribute for each of the occupants.

The *drive* is a measure of the assertiveness of an occupant and is part of the occupant attribute parameter set.

(iii) Direction changes - occur as a result of three factors, cabin crew influence, queuing/crowding and hazard concentration. Whenever an occupant is forced to remain stationary, for example due to crowding, the amount of time they remain stationary - known as wait time - is recorded. When an individuals wait time exceeds a critical level - defined by their patience attribute - the occupant attempts either to go around the blockage or move away, possibly towards another exit.

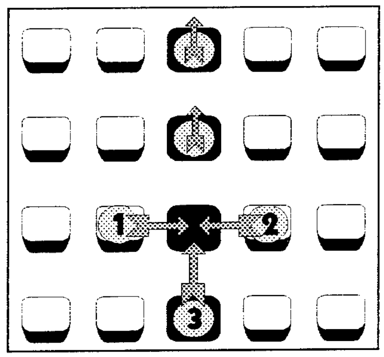

FIGURE 3: air-EXODUS Conflict Resolution.

(iv) Overtaking - occurs as a natural consequence of the movement rules, specific overtaking algorithms are not required. An occupant blocked by a slower moving occupant will attempt to find an alternative neighbouring empty nodal position within the direction of travel.

(v) Obstacle jumping - in the form of seat or debris jumping occurs when an occupant's wait time exceeds their patience and their agility attribute will allow them to do so. It is behaviour usually displayed by occupants caught between seats while aisles are blocked.

(vi) Exiting procedure - is dependent on two factors, exit width and exit hesitation time. The exit width determines the maximum number of people which can pass through the exit simultaneously. The exit hesitation time is used to determine the delay each occupant is likely to experience in passing through the exit. The exit hesitation time may be obtained using one of three methods, the software can predict the hesitation time on the basis of its rules, it can be prescribed through the use of historical or experimental data and finally, a combination of rules and experimental data can be used. Access to exits and congestion around exits while exerting a strong influence on overall exit flow rates are handled by features of the model previously described.

4.0 FACTUAL DATA RELATING TO EVACUATION MODELS

Associated with the development of computer based aircraft evacuation models is the need for comprehensive data

collection/generation related to human performance under evacuation conditions.

Factual data regarding the evacuation process is essential to the development of computer egress models. While specifically addressing the data requirements of air-EXODUS, other aircraft evacuation models [14] have a similar reliance on data. Every component of the evacuation model just described relies on input from the real world in order to,

a) identify the physical, physiological and psychological processes which contribute/influence the evacuation process and hence formulate the appropriate rules,

b) quantify attributes/variables associated with the identified processes and finally,

c) provide data for model validation purposes.

The following is a list of data/information which is necessary for the development of aircraft evacuation models. While it is not definitive it addresses each of the three areas listed above.

1) Exiting Procedures: Develop relationships describing measured exit delay times for particular exit types related to gender/size/age and nature of exiting method i.e. slide or platform.

2) Occupant Behaviour: Observation and characterisation of occupant behaviour, in particular, (a) route planning, (b) exit path recommitment, (c) influence of travel companions on behaviour and (c) change in behaviour dynamics as a function of increasing smoke density, reduced lighting, single or multiple aisled geometries.

3) Physiological Response: Establish which - if any - of the existing narcosis and irritant gas models is appropriate for use in aircraft fire situations and develop a linkage between passenger attributes and level of exposure to irritant and narcotic gases.

4) Response Times: Data which characterises the range of occupant response times for a variety of age/gender/agility groups. In particular need to consider, (a) time to release seat belts, (b) time required to assist others and (c) effect of smoke/darkness.

5) Travel Speeds: Data which characterises the range of occupant travel speeds for a variety of age/gender/agility groups. In particular need to consider travel speeds, (a) from window seat to aisle, (b) along aisle, (c) over seats, (d) over obstructions. This data can be characterised for level cabin floors, sloped cabin floors, as a function of smoke density (similar to the work of Jin and Yamada 1988) and in reduced light conditions.

6) Validation Data: Provide full-scale evacuation data from single and twin aisled configurations suitable for the validation of evacuation models.

Three forms of existing data are expected to provide some of the required information. Aircraft accident human factors reports produced by for example the NTSB and the AAIB (see 4.1), 90 second certification data held by the aircraft manufacturers (see 4.2), and large-scale experimentation devised to answer operational questions (see 4.3). Gaps in the knowledge this information provides can be filled by a combination of large- and small-scale targeted experimentation.

4.1 The AASK Data Base of Survivor Statistics

Information from the first source is currently being collected by researchers from the Fire Safety Engineering Group (FSEG) at the University of Greenwich. The information is being collated into a database known as AASK which is an acronym for Aircraft Accident Statistics and Knowledge. At present, detailed information from NTSB and AAIB reports are being loaded into the database. This information is being collected from documented accounts of survivor interviews and factual reports.

Two types of passenger information is being collected. These involve:

(1) Simple factual information, for example,
- which exit passengers used,
- location of fatalities and where they started from,
- location and nature of cabin debris.

(2) Passenger/Crew accounts of behaviour, for example,
- how quickly occupants responded,
- difficulty with seat restraints,
- path taken to exit,
- did they encounter difficulty entering aisle?
- did they go over seat backs?
- did they recommit after selecting a particular exit,
- did they experience difficulty seeing or breathing.

The database can be used to analyse a single accident or a collection of accidents. As an example of the type of analysis which can be performed consider the following exit usage analysis performed on several of the accidents currently in the database.

Consider the B727 accident at Dallas on 31 August 1988 [15]. The aircraft crashed shortly after takeoff and was eventually destroyed by a postcrash fuel fire. The passengers and crew used two serviceable exits and three fuselage ruptures to make their escape.

Of the 89 survivors 81 passengers or 91% filled in a report. Of the 81 passengers reporting their exit usage only 18 passengers failed to use their nearest serviceable exit/opening. Of these passengers, nine passengers supplied reasons for this action. Three passengers were not aware of their nearest exit, two passengers decided that the congestion

at the exit was too great and decided to try another, and four passengers were following someone else.

A similar analysis was performed over 16 accidents since 1982 and involved responses from 616 passengers or 49% of the survivors. The 16 accidents involved incidents during take-off (7) landing (5), post take-off (1), mid-flight (2) and parked (1). The aircraft involved in these accidents ranged from small commuter aircraft to wide-body aircraft. Of the 616 passengers who reported their exit usage 125 (20%) passengers failed to use their nearest serviceable exit. Of these, 77 (12.5%) passengers failed to supply any reason for their actions. The remaining 48 passengers gave the following reasons for not using their nearest exits, 22 reported following the Flight Attendants instructions (i.e. re-direction), 11 simply followed other passengers, 5 reported congestion at the nearest exit, 1 reported a fire in the vicinity of the exit, 6 thought that the nearest exit was blocked and 3 were not aware of the nearest exit.

While not complete, this analysis suggests that 98% of those reporting their behaviour used or had a good reason for not using their nearest serviceable exit.

This type of analysis is extremely valuable in aiding our understanding of the behaviour of people in real accidents and as such addresses the requirements of item (a) listed above and to a lesser extent item (b). It also provides essential insight to modellers attempting to simulate the evacuation process. While not yet complete, the analysis just described provides some justification for adopting the global behaviour described in air-EXODUS and the nature of the local behaviour override. Detailed investigation of this type may also highlight behaviour which can be further examined through experimentation.

4.2 Manufacturers 90 Second Certification Trial Data.

A further source of potentially useful data has been collected by the aircraft manufacturers through the certification process. While the relevance of certification data to the development of models attempting to simulate evacuations under 'real' conditions may be questionable, its relevance to the development of evacuation models capable of simulating certification conditions is obvious. Furthermore, in the absence of more relevant data this information is vital. However, access to this data is difficult due to its propriety nature. The FSEG in conjunction with the UK CAA have undertaken a study of the manufacturers 90 second certification data. To date, BOEING, MDC, BAe and deHavilland have made all their 90 second data available for study. AIRBUS INDUSTRIE have agreed in principle to make their data available.

The data being extracted from this information is useful for all three of the above areas. For example, by studying video footage of certification demonstrations it is possible to collect information describing human behaviour such as,

- do passengers encounter difficulty entering aisle from seat?
- do passengers queue in aisles? if so for how long and where did the congestion occur? What is the nature of the congestion? What was the cause of the congestion?
- do passengers go over seat backs? If so, why? exit and entry points noted.
- do passengers recommit after selecting a particular exit,
- do exits become congested?
- quantify passenger hesitation at various exit types,
- is the behaviour of passengers under reduced lighting conditions significantly different to that expected under normal lighting conditions?

This information partially addresses item (a). Detailed analysis of video footage is also useful in quantifying attributes/variables used in the evacuation model thereby providing input to item (b) identified above. For example it is possible to extract information relating to,

- how quickly passenger's respond to evacuation call,
- estimates of passenger maximum travel speeds,
- estimates of delay times at exits.

Finally detailed information concerning exit usage and evacuation times is useful for validation purposes thereby addressing item (c). While the study has only just begun, the information is proving extremely valuable.

4.3 Large- and Small-Scale Evacuation Experiments.

The third source of existing data is provided by large- and small-scale evacuation experiments. Over the past six years, the UK CAA has sponsored a series of large-scale competitive evacuation trials from a single aisled aircraft using a single exit [16]. These trials were designed to answer specific operational questions concerning passenger behaviour relating to exit width and seat spacing at exits. This work has recently been extended to include competitive evacuations through multiple exits and the role of cabin crew intervention [17]. This research is on-going and forms part of an international collaboration between the UK CAA and the USA FAA. Unfortunately, no detailed information of this type currently exists concerning competitive evacuations from wide-body aircraft.

To date most - if not all - the experimental effort in human evacuation research has been directed towards answering specific operational questions. Wherever possible this data has also been used to assist in the development of computer based evacuation models by providing insight into competitive human behaviour, more importantly however, they contribute to the general pool of data for model validation purposes. Thus, the data from this type of experimentation provides information which partially addresses item (c) above and to a lesser extent item (a). Information from the Cranfield trials for example is being used as part of the EXODUS validation procedure (see figure 4). Other experimental research involving large-scale evacuation can provide detailed information to quantify essential model parameters and thereby address the requirements of item (b) listed above. For instance, recent work conducted by FAA CAMI has correlated the delay time

associated with passengers of various weights, heights and genders, on passing through Type III exits [18]. This data has been included within the EXODUS model as part of the exiting procedure options.

5.0 air-EXODUS SAMPLE SIMULATIONS

To demonstrate the capabilities of the air-EXODUS evacuation model several sample simulations will be presented. These simulations are not intended to demonstrate the hazard or toxicity submodel and so the scenarios simulated will be free of fire hazards. Sample simulations of air-EXODUS including the effects of fire hazards may be found in references [4,5,6]. The following examples involve a simulation of one of the CRANFIELD trials involving two exits in the B737 simulator (see 5.1) and the predictive calculations of several 90 second certification results (see 5.2).

5.1 air-EXODUS Predictions of Cranfield B737 Evacuation Trial.

air-EXODUS is being used to simulate the evacuation trials conducted by CRANFIELD in their B737 simulator. The cabin section consists of the front two Type I exits, and 60 passengers distributed over the first 10 rows of seats. The specific trials presented here involved competitive evacuations with both Type I exits and two assertive cabin crew [17]. The experimental trials were repeated four times with the experimental results producing a spread in evacuation times (see figure 4).

The extremes in evacuation performance were used to define an experimental window of acceptable results, denoted by the solid straight lines in figure 4. The situation was then modelled using air-EXODUS. The results from four repeats of air-EXODUS are also shown in figure 4 and are denoted by the stepped curves. Clearly, the air-EXODUS simulations fall within the variation observed in the experiment.

5.2 air-EXODUS Predictions of Boeing 767 Certification Trials.

On April 13 1996 Boeing successfully performed a 90 second certification trial on a modified B767 aircraft, designated the B767-304ER. This aircraft was configured with three pairs of Type A exits similar to those found on existing B767 aircraft and one pair of Type I exits similar to those found on B757 aircraft. The UK CAA requested that FSEG perform a series of predictive simulations using the air-EXODUS model for this aircraft prior to the actual test inorder to establish whether or not air-EXODUS was capable of accurately predicting the outcome of 90 second certification trials. Three confidential reports [19,20,21] containing details of the model formulation and results of the simulations were produced by FSEG and distributed to the UK CAA and US FAA prior to the trials, and Boeing after the trials. Here we briefly present some of the preparatory simulations and a description of the results for the B767-304ER.

5.2.1 Preparatory Analysis

In order to make air-EXODUS model predictions for the B767-304ER meaningful, a considerable amount of data analysis was performed prior to the test. Prior B767 (B767-200 and B767-346) and B757 certification data - including video footage of the actual trials - was analysed (as part of the project described in 4.2). This analysis included such aspects

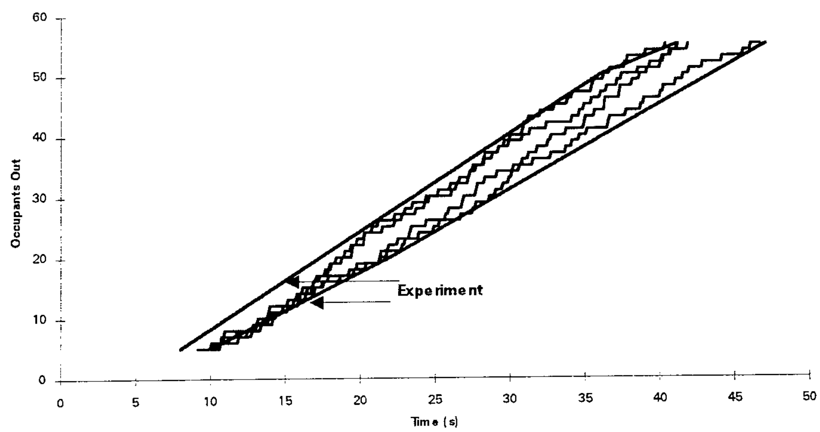

FIGURE 4: Evacuation curves depicting air-EXODUS predictions (stepped curves) and experimental envelope derived from Cranfield trials (B737 simulator) involving two forward exits and two assertive cabin crew.

Table 1: air-EXODUS evacuation times using optimal exit distribution for the 767 series 346.

	Aft (A)		Fwd O/W (III)		Aft O/W (III)		Fwd (A)	
	No	Time	No	Time	No	Time	No	Time
min	106	**69.9**	41	66.9	47	67.6	91	64.1
max	106	**76.9**	40	67.3	48	67.8	91	69.1

as crew performance (i.e. level of assertiveness), door opening times, slide times, etc. The primary purpose of this analysis was to establish a range of approximate exit hesitation times suitable for Type A, Type I and Type III exits [19].

As described in section 3.2.6 (vi) air-EXODUS requires the exit hesitation time as part of the data entry to characterise an exit. The exit hesitation time for Type I and A exits represents the delay a person experiences between standing on the door sill and transferring onto the slide. Some passengers jump from the sill to the slide in the correct manner - experiencing a small delay - while some passengers sit on the sill before pushing themselves onto the slide - experiencing a longer delay - while others freeze momentarily before moving onto the slide - very long delay. The delay time is dependent on a number of factors including type of exit, height above the ground, size, age, weight and gender of passenger, assertiveness of cabin crew etc. In air-EXODUS it is possible to specify the exit hesitation times in a number of ways depending on the quality of the data. It is possible to specify a minimum and maximum hesitation time for each exit type and randomly assign each passenger with a hesitation time according to the limits. If more data is available a functional form describing the hesitation time distribution is possible. As an indication of the range of hesitation times noted for Type A exits, passengers were observed to hesitate from a few tenths of seconds to several seconds.

This data was extracted from the initial analysis [19] and as a first test applied to the prediction of the previous B767-200 and B767-346 certification trials [20]. A number of different scenarios were performed, these were intended to simulate efficient and inefficient evacuations. Among the options considered were allowing the passengers to head towards their nearest serviceable (inefficient) and allowing passengers to head towards the optimal exit. A summary of the optimal model predictions for the B767-346 are presented here.

The B767-346 has two pairs of Type A exits and a pair of dual Type III exits over the wing. The aircraft seats 285 passengers. The aircraft configuration used in the certification trial was constructed in air-EXODUS using the interactive geometry tools. For each of the simulations, the exit opening times used in the air-EXODUS trials are the actual times recorded for the opening of each particular exit. In the simulations presented here, the exit hesitation times were assigned using a uniform random distribution between the observed maximum and minimum values. Each case examined was repeated a number of times. The repeats were associated with a random re-seating of the passengers. In the results presented note that,

(i) All times refer to evacuation times for passengers only. Crew evacuation times are not included.

(ii) Exit opening times correspond to the actual values achieved in the trial.

(iii) All times refer to the time to exit the aircraft and so do not include slide times i.e. on ground times.

Table 1 shows the minimum and maximum evacuation times achieved for the B767-346 aircraft. The model predicts an evacuation time of between 69.9 and 76.9 seconds, with an average over 12 trials of 72.9 seconds (excluding crew and slide times). The predicted overall evacuation time was within 2% of that achieved in the trial. Results for the B767-200 were predicted to an identical level of accuracy.

5.2.2 Blind Predictions for the B767-304ER.

Following the success of the B767-200 and B767-346 predictions, air-EXODUS was used to predict the performance of the new B767-304ER prior to the actual test [21]. The geometry of the B767-304ER was constructed within air-EXODUS using the interactive geometry mode. The geometry is based on dimensions and seating configurations supplied by Boeing. The aircraft seats 351 passengers. The exits are arranged with two pairs of Type A exits forward of the wing, a pair of Type I exits just aft of the wing and a pair of Type A exits in the rear of the aircraft. For the purposes of the simulations, all four exits on the right side of the aircraft are used in the evacuation.

A total of 321 evacuation simulations for the B767-304ER were produced using the air-EXODUS evacuation model. As in the previous cases all times quoted are for passengers only and do not include passenger slide or crew evacuation times. In the results presented here all exits were made ready after a delay of 10 seconds.

Two types of scenario were investigated. Each case examined was repeated at least four times. The repeats were associated with a random re-seating of the passengers. The first scenario involved passengers heading towards the exit which is deemed optimal. An optimal selection of exits may necessitate some passengers using an exit which is not necessarily their closest exit. These cases give an indication of the best times that can be achieved by crew and aircraft during the trial assuming all goes well. A number of sub-optimal cases were also run. These cases give an indication of times which may be achieved if problems are encountered during the trial. Scenarios investigated included late opening of exits and inefficient crew performance resulting in poor passenger distribution between the available exits.

In order to specify various levels of sub-optimal performance it is necessary to define a parameter which measures optimal performance. In aircraft which have more than one exit available for evacuation, the total evacuation time will typically be reduced if the flow through each exit terminates at the same time. Failure to achieve the simultaneous termination of exit flows is usually a result of poor distribution of passengers between exits which in turn results in an unnecessarily prolonged evacuation time. Note that no mention of the number of passengers using each exit is made, simply that the flow through each exit terminates simultaneously.

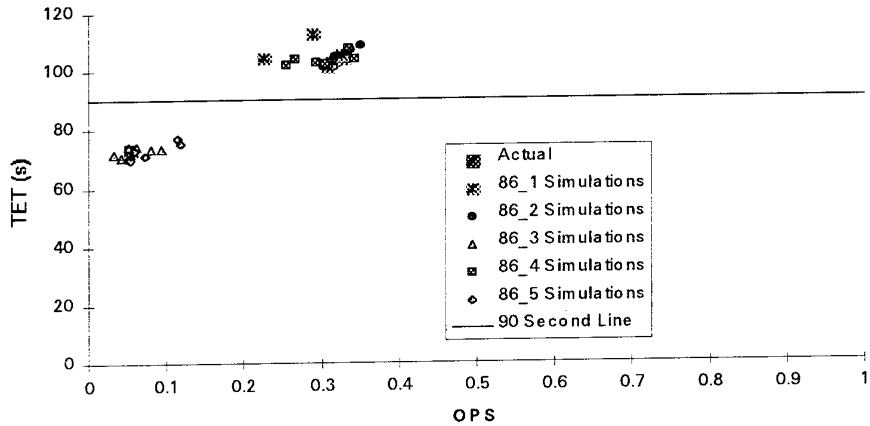

FIGURE 5: air-EXODUS generated evacuation time (seconds) versus OPS graph for the B767-346.

Thus in optimal evacuation situations exit flows will be completed at approximately the same time. Sub-optimal cases occur when one or more exits exhaust their supply of passengers before the remaining exits. Reasons for sub-optimal performance are many and varied and can be due to poor evacuation procedures, poor cabin crew performance, equipment failure, unusual passenger behaviour, poor cabin design and layout or a combination of all these factors.

As a measure of optimal performance we have developed a statistic known as the OPS or Optimal Performance Statistic. The OPS can be calculated for each evacuation, providing a measure of the degree of performance. The OPS is defined as follows,

$$OPS = \frac{\sum_{i=1}^{n} TET - EET_i}{(n-1) * TET}$$

where,

n = number of exits used in evacuation

EET_n = Exit Evacuation Time (time last passenger out) of Exit n (seconds)

TET = Total Evacuation Time (seconds) = max[EET]

An evacuation in which OPS = 0 indicates an optimal (or perfect) distribution of passengers was achieved.

An evacuation in which OPS = 1 indicates the worst possible distribution of passengers in which every passenger used a single exit thereby ignoring all other exits.

An OPS value greater than zero is sub-optimal indicating that the evacuation time can be improved by achieving a better distribution of passengers or better crew performance etc.

While it is unlikely that an aircraft will achieve an OPS = 0, near optimal performance will be marked by low values of OPS. As an example consider the performance figures for the B767-346 predicted using air-EXODUS. The results reported in table 1 were reported to be optimal.

From table 1 using the minimum set of results,

EET_1 = 66.9s, EET_2 = 67.6s, EET_3 = 64.1s and TET = 69.9s (ignoring crew times and slide times).

Substituting these values into the OPS expression results in,

$$OPS = [(69.9 - 66.9) + (69.9 - 67.6) + (69.9 - 64.1)]/[69.9*3]$$
$$= 0.05$$

If the calculations are repeated using the maximum times we find OPS = 0.11

Aircraft and crew in both cases achieved OPS values near zero and hence both produced near optimal performance.

A plot of evacuation time versus OPS can suggest how the evacuation performance may be improved. Figure 5 presents a plot of evacuation time versus OPS for the air-EXODUS predictions of the B767-346. Clusters in the bottom left represent desirable outcomes - aircraft and crew achieve sub-90 second evacuation times and an optimal OPS. These aircraft have an efficient cabin layout and crew. An aircraft which fails the 90 second evacuation criteria but achieves a near optimal OPS (clusters in the top left) can not be expected to achieve better evacuation performance through improved passenger distribution. Performance may be improved either through improved aircraft design (e.g. exit capacity or exit approach) or through improved crew performance at the exits (i.e. greater assertiveness). Conversely, an aircraft which fails the 90 second evacuation criteria and achieves a sub-optimal OPS (clusters in the top

right) can be expected to achieve better performance through improved passenger distribution. This may require improved crew procedures, improved crew performance, more crew, improved cabin layout etc. An aircraft which passes the 90 second evacuation criteria and achieves a sub-optimal OPS (clusters in the bottom right) has excess exit capability and/or a poor distribution of passengers/exits (i.e. cabin layout).

Selecting an acceptable value for OPS is somewhat arbitrary. From the B767-200 and B767-346 EXODUS simulations, OPS values less than 0.12 produced efficient evacuations, while in the actual trials each aircraft achieved an OPS value of 0.05. For the purposes of the B767-304ER predictions, OPS values less than to 0.1 are considered optimal.

The results presented in table 2 represent a selection of the optimal (OPS<0.1) predictions.

These results suggest,

(1) The B767-302ER is capable of producing evacuation times in the range from 69.5 to 74.4 seconds with an average of 71.8 seconds. Each case produced an OPS < 0.084, satisfying our optimality criteria.

(2) The average exit usage is distributed as follows,

AR 98 passengers, MAR 62 passengers, MFR 95 passengers and FR 93 passengers.

TABLE 2: air-EXODUS predictions for B767-304ER (note: times exclude slide times and crew times).

AR		MAR		MFR		FR		TET (sec)	OPS
# pax	**time (sec)**	**# pax**	**time (sec)**	**# pax**	**time (sec)**	**# pax**	**time (sec)**		
99	68.4	63	69.5	98	**70.5**	91	65.7	**70.5**	**0.037**
98	70.6	63	**70.6**	99	69.5	91	63.5	**70.6**	**0.039**
98	64.8	63	71.4	98	**72.2**	92	63.6	**72.2**	**0.078**
97	72.5	60	66	95	68.7	99	**74.4**	**74.4**	**0.072**
97	67.5	62	69.8	99	**73.7**	93	73.6	**73.7**	**0.046**
97	65.9	63	69.7	97	**71.6**	94	67.6	**71.6**	**0.054**
100	**72.7**	63	68.7	89	66.7	92	64.6	**72.7**	**0.083**
100	67.9	63	**70.7**	88	68.8	93	66.9	**70.7**	**0.040**
100	**69.5**	62	66.4	90	68.6	92	67.2	**69.5**	**0.030**

(3) The last exit to finish was distributed amongst the various exits as follows,

AR 22%, MAR 22%, MFR 45% and FR 11%.

A thorough comparison of model predictions with actual test results is not yet possible as the detailed information from the trial is not yet available. The evacuation times reported for the trial are,

AL 73.2 seconds, 113.3 ppm, MAL 72.5 seconds, 62.9 ppm, MFR 68.5 seconds, 109.6 ppm and FR 75 seconds, 89.0 ppm.

These times include slide times and the time for the crew to evacuate. In order to make a direct comparison with the model predictions the time for the crew to leave the aircraft and the slide times must be subtracted from the above times. This will require an analysis of the video footage of the trial. It can however be estimated from the recorded exit flow rate in passengers per minute (ppm), the number of crew to use each exit and allowing 2 seconds for slide times. This produces the following estimated times for the trial, AL 70.1 seconds, MAR 68.6 seconds, MFR 65.4 seconds, and FR 70.3 seconds, and an OPS value of 0.032.

The OPS value achieved in the trial indicates that this evacuation was very efficient and achieved the same level of optimality as achieved in air-EXODUS.

This suggests that the average evacuation time predicted by air-EXODUS is within approximately 2% of the measured time. Furthermore, general trends in passenger flow behaviour predicted by air-EXODUS appear to have been corroborated by actual events, for instance, the passenger split within the cabin predicted by air-EXODUS was achieved in the actual trial.

6. CONCLUSIONS

In this paper we have attempted to describe possible enhancements to the current evacuation certification process. Evacuation models have been suggested as a possible alternative to the current practice of performing a single evacuation demonstration with live people. The demonstrated success of the air-EXODUS evacuation model in predicting the outcome of a recent evacuation trial prior to the actual event is a compelling argument of the use of computer models for evacuation certification - at least for derivative aircraft. For truly 'new' aircraft configurations involving new hardware features such as a new type of exit, it is expected that evacuation models in conjunction with component testing of the new feature will offer a sensible and reliable alternative to full-scale live evacuation trials. However, more validation of evacuation models is required before they can be accepted as a reliable general alternative to evacuation

trials. Validation of the air-EXODUS evacuation model is continuing through the simulation of past 90 second certification trials.

While the regulatory authorities may require further evidence of the benefits offered by evacuation models for certification purposes, aircraft manufacturers and aircraft operators should exploit this technology as an aid in the design of new aircraft and in the development of cabin crew procedures and training of cabin crew. In addition, features of the air-EXODUS model not demonstrated in this paper, such as the impact of smoke, heat and toxic fire gases on the passengers, make the model useful as an aid to the investigation of real accidents. Furthermore, these features can also be used for design, bringing issues such as the impact of smoke on the evacuation into the design phase.

Work on the air-EXODUS model is continuing with the development of new features such as explicit modelling of cabin crew - including the specification of primary and secondary duties, and the development of a virtual reality visualisation capability. Data analysis is also continuing with the further development of the AASK data base and the analysis of aircraft manufacturers 90 second certification data.

7. ACKNOWLEDGEMENTS

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DISCUSSION - PAPER NO. 36

E. Schwartz (Question)

1) Have you collected any data for the AASK database, other than from CAA, NTSB, specifically incidents such as in Japan - Garuda Indonesian Airlines accident (foreign language problem in evacuation)?

2) What is the availability of airEXODUS (public domain)?

E.R. Galea - Author/Speaker (Response)

1) We have attempted to obtain reports from other authorities, but with no success. However, the point you raise concerning foreign language is a real issue. We have seen suggestions of it in reports produced by the NTSB. If anyone has access to reports concerning accidents such as the Japan-Garuda accident we would greatly appreciate receiving a copy.

2) The development of airEXODUS is being sponsored by several organisations, primarily the UK CAA and the University of Greenwich. All those involved in the airEXODUS project have an interest in seeing that it is widely available and used in a correct and responsible manner.

While airEXODUS is still undergoing development, the authors are in a position to use the software in an advisory role for aircraft manufacturers and airlines. In fact, airEXODUS has already been used on several projects. A version will be available for limited distribution to users who can usefully contribute to its further development in the December 1996 / January 1997 time frame. Interested parties should contact the author at the University of Greenwich.

It is expected that a version will be available for general release sometime in 1997, together with a comprehensive user guide and technical manual which states the key model assumptions and limitations. The developers also expect to offer software support and user courses covering the principles of the software and its correct use. However, at this stage, there are several issues concerning the distribution of airEXODUS remaining to be resolved between the model developers and their sponsors.

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Fluorohydrocarbons	Tests
Aircraft explosions	Passenger aircraft
Fire extinguishing agents	Protective equipment
Toxicity	Halon
Human behaviour	Passengers

14. Abstract

The Propulsion and Energetics Panel Symposium on Aircraft Fire Safety was held in Dresden, Germany from 14-17 October 1996. It dealt with military and civil aspects of fire safety, covering combat-induced damage and technical sources of fire, fire prevention, fire fighting, fire damage control and fire damage to humans and equipment.

Environmental issues including Halon replacement were addressed. There were 7 sessions (37 papers) and a keynote address:

Aircraft Fire Safety (4);
Fires and Fire Handling (6);
On-board Fire Extinguishing Systems (6);
Certification and Testing (6);
Materials and Structure Design for Fire Safety (5);
Aeromedical Aspects Including Smoke Toxicity (6);
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